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FOR A STREAMBANK STABILIZATION PROGRAM
FOR THE BITTERROOT RIVER, MONTANA

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A FEASIBILITY STUDY FOR A STREAMBANK STABILIZATION PROGRAM FOR THE BITTERROOT RIVER, MONTANA

Prepared for

Water Resources Division
Montana State Department
of Natural Resources and Conservation
Helena, Montana

by

Daryl B. Simons
Principal Engineer

Ruh-Ming Li
Principal Hydraulic Engineer

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Watershed Biologist

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Simons, Li & Associates, Inc.
PO Box 1816
Fort Collins, Colorado 80522

January 16, 1981

Study of Bitterroot River by Darryl Simons

Purpose: To find out what measures are possible to stabilize river. (Particularly between Corvallis & Stevensville).

Remedial Actions:

Non-structural - public awareness
District Request - Management Practice
Guidelines for Bitterroot

100 yr. flood plain - aggradation or degradation does not necessarily mean there is a change in the 100 yr. flood plain. Nor does it mean difference in change.

MT-ENG-119 (Rev.)
11/68

SOIL CONSERVATION SERVICE
SPRINKLER IRRIGATION - Design Guide

Name ______________ Address ______________ Field No. ______________

Acres To Irrigate 134 Water Supply ______________ Crop(s) To Be Grown ______________

SOIL

1. Type (Description and Texture) ______________
*2. Depth ________ Ft.
*3. Max. Intake Rate ________ In/Hr.
*4. Total moisture holding capacity of soil ______________

CROP

*5. Root zone depth of major crop ________ Ft. (If more than one crop is anticipated, each crop should be considered in the design).
*6. Moisture extraction depth (Use smaller value of Line 2 or Line 5 ________ Ft.
*7. Water holding capacity in extraction depth ________ In.

GENERAL LAYOUT

*8. Net moisture to be replaced 2.75 In.
*9. Field efficiency 70 ~~.70~~ %
*10. Gross application is Line 8 divided by Line 9 = 3.92 In.
*11. Peak moisture use/day by crop .25 In.
*12. Maximum Irrig. Frequency is Line 8 divided by Line 11 = 11 Days
*13. System Cap. Q = $\frac{(453AD)^{**}}{FH}$ 920 gpm.

Say 1000

SYSTEM DESIGN

14. No. of hours per set 11.5
15. Application Rate = $\frac{\text{Gross application}}{\text{No. hrs. per set}}$ = .356 In/Hr.
16. Sprinkler head spacing ______________
17. GPM/hd. to meet application rate ______________
18. Sprinkler head model ______________
19. Nozzle sizes ______________
20. No. of heads in system ______________
21. Total GPM ______________

NOTE: Items 8, 10 & 12 are maximum values. These can be decreased as long as the peak moisture use per day in Item 11 is satisfied. Item 13 is a quick check on adequacy of minimum system capacity. Odd shaped fields should meet capacity in Item 21.

PUMPING HEAD

22. Sprinkler Operating Pressure PSI 45 = 105 Ft.
23. Suction Lift 10 Ft.
24. Elevation Beyond Pump 50 Ft.
25. Friction Loss - Suction Line ________ Ft.
26. Friction Loss - Main Line ________ Ft.
27. Friction Loss - Lat. Line ________ Ft.
28. Head Loss - Other ________ Ft.
29. Total Head [illegible] Ft.

PUMP & POWER UNIT

Type of power unit ______________
Size of pump ______________
Make & No. ______________
Efficiency of pump & power unit ______________
BHP Required = $\frac{\text{GPM x Head in Ft.}}{\text{3960 x efficiency}}$ = $\frac{1000 \times [illegible]}{3960 \times .7}$ = 12[illegible]

$\frac{920 \times 170}{3960 \times .75} = 52HP$

Say 60 HP

= 44.76 KW

× 2000 ~~kw~~ Hr

= 89,520 KHr

$1969

= $1470

* Irrigation Guide should be consulted for these values.

** $Q = \frac{453AD}{FH}$

Q = Discharge capacity in gallons per minute.
A = Acreage of design area.
d = Actual cross application of system.
F = Number of days required for one irrigation (actual irrigation frequency).
H = Number of actual operating hours per day.

Instructions On Use Of Form

In consultation with cooperator, SCS will fill out items 1 through 13 and Items 23 and 24. Cooperator furnishes this information to supplier who furnishes sprinkler design to meet these requirements. Where cost sharing is involved, the SCS will check the supplier's design.

UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
111 Old Corvallis Road
Hamilton, Montana 59840

March 12, 1981

Daryl B. Simons
President and Principal Engineer
Drake Creekside Two
2625 Redwing Road Suite 350
Fort Collins, Colorado 80522

Dear Daryl,

Enclosed please find the corrections and support data for some errors in "A Feasibility Study For A Streambank Stabilization Program for the Bitterroot River, Montana" as we discussed Thursday afternoon, February 26, 1981. I hope these will be of help to you. Please feel free to contact me if you have further questions.

Sincerely,

Stephen G. Durgin

STEPHEN G. DURGIN
Civili Engineer

encls:

cc: Forrest Berg

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1. Cost of rock rip rap in place in the Bitterroot Valley runs about $30 - $40 per running foot.

   Generally costs are about $10/ cu. yd. in place.
   Using 2.5 cu. yd./ft, total cost per foot would be $25.
   Installing adequate filter blanket may cost another $5 per foot.

   As an example, rip rap on a current project up in Libby, MT is currently running about $60 / ft. On this project about 5 cu yds / ft are being used. Rock is more expensive in the Libby area than in the Hamilton area.

2. The power costs to irrigate an acre of ground runs about $10 - $20 per acre, $10 per acre for larger tracts ranging to $20 per acre on smaller tracts. These values were determined from interviews with more than 80 land owners in the 3-Mile area in July of 1980 and by information from the REA.

Compare the example used in support text pp. 141-142 with a more typical set of values for this valley.

	Text Example	Local Example
Acres Alfalfa	134 Acres	134 Acres
Consumptive use/yr	34 inches	23 inches
Irrigation required/year	27 inches	17.5 inches
Efficiency	85 %	65 %
Pumping Requirement/year	32 inches	27 inches
Flow needed	1000 gpm	1000 gpm
Hrs. needed/yr (Pumping reqd) x (acres)	$\frac{32 \times 134}{1000} \times \frac{452 \text{ gpm}}{\text{Ac. in/hr}}$	$\frac{27 \times 134}{1000} \times \frac{452 \text{ gpm}}{\text{Ac in/hr}}$
	1938 hrs.	1635 hrs.
Total Dynamic Head (TDH)	360 ft.	170 ft.
Horsepower (HP) $\frac{\text{GPM} \times \text{TDH}}{\text{Efficiency} \times 3960}$	$\frac{1000 \times 360}{.75 \times 3960}$	$\frac{1000 \times 170}{.75 \times 3960}$
	121.2 HP	57.2 HP
	Use 140 HP	Use 60 HP
Kilowatt Hours (Kw Hr) $\frac{\text{HP} \times \text{Hrs.}}{1.34 \text{ HP/KW}}$	$\frac{140 \times 1938}{1.34}$ 202,478 Kw-Hr	$\frac{60 \times 1635}{1.34}$ 73,209 Kw Hr

Cost/KW	$.0427	$.02
Total Cost Electricity	$8,645.81	$1464.18
Total Cost Electricity/Acre	$ 64.52	$ 10.93
O + M on Pump/Acre 15% of electricity cost	$ 9.68	$ 1.64
Total Cost/Acre Electricity + O/M	$ 74.20	$ 12.57

3. In light of the lesser Kw/hrs/acre used in the local example, the cost/acre of gas or diesel powered irrigation should be far less than indicated in the text. Also, the cost for gabions, soil - cement and grouted rock may also be quite high.

SIMONS, LI & ASSOCIATES, INC.

POST OFFICE BOX 1816
DRAKE CREEKSIDE TWO
2625 REDWING ROAD SUITE 350
FORT COLLINS, COLORADO 80522

TELEPHONE (303) 223-4100

February 17, 1981

Mr. Richard Ormsbee
Bitterroot Conservation District
111 Old Corvallis Road
Hamilton, MT 59840

Dear Dick:

Enclosed please find a personal copy of our Technical Report "A Feasibility Study for a Streambank Stabilization Program for the Bitterroot River, Montana." We have sent this report as a small measure of our appreciation for your help during our visit to the Bitterroot area in the early stages of the project.

As requested by Chris Hunter, we have also sent you 20 copies of our Summary Report for public distribution. I hope to personally be able to attend the public meeting in early March and look forward to seeing you then. Once again, thank you for your help and guidance in getting the project off to a good start.

Sincerely yours,

Daryl B. Simons

Daryl B. Simons
President and Principal Engineer

DBS/jb

Enclosure

cc: R. M. Li
S. S. Ellis
J. D. Schall

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ACKNOWLEDGMENTS

Many people provided assistance in preparing this report, and without their help we could not have completed the study in such a short time. Initially, we would like to thank Mr. Chris Hunter and other staff of the Department of Natural Resources and Conservation, State of Montana, for their guidance and input throughout the study. Additionally, people in the Bitterroot area were particularly friendly and helpful during the collection of initial information and data. Specifically, we would like to offer thanks to Mr. Leonard Peterson, Mr. Dick Ormsbee and Mr. Tom Murphy of the Bitterroot Conservation District, who familiarized us with the Bitterroot area and assisted us in obtaining many informative documents. Also, Mr. Bob Hammer and Mr. L. M. Powell of the Bitterroot National Forest supplied us with specific information and data necessary to conduct the study. Finally, Mr. Don Peters of the Montana Fish and Game Department and Mr. Andy Carlson coordinated our float trip. The cooperation of these people and others greatly expedited the study and helped to develop a strong data base.

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EXECUTIVE SUMMARY

The Bitterroot River is a dynamic river that has experienced substantial channel alteration during the past years. Widely varying natural climatic and hydrologic conditions, as well as human activities, will continue to change the configuration of the Bitterroot River channel. Naturally occurring bank erosion is common in dynamic alluvial river systems, but certain conditions can amplify the erosion process. The instability of the Bitterroot River channel is the result of a combination of causes. Methods used to investigate the instability problem include: (1) inspection of the river system by visiting the area, (2) a review of the geology of the area, (3) interpretation of climatic and hydrologic data, (4) a historical review of land use practices, (5) analyses of sediment transport and aggradation or degradation tendencies, (6) geomorphic classification of the river, (7) analysis of aerial photographs, and (8) application of geomorphic, engineering, environmental and economic principles to the system.

Aerial photographs of the reach between Hamilton and Stevensville were examined for the years 1937, 1940, 1964, 1972, 1976, and 1979. Hydrologic data from the United States Geological Survey (USGS) and the Montana Department of Natural Resources and Conservation (DNRC) gaging stations, including precipitation, snowpack, and discharge data for the period of record, were used to identify climatic trends. Sediment transport calculations were based on state-of-the-art methods. A general knowledge of the physical processes of geomorphology, hydrology, hydraulics and sediment transport was applied to interpret observations and calculations. This procedure resulted in specific conclusions regarding problems of channel instability in the Bitterroot River.

The Bitterroot River is a braided stream flowing through coarse glacial detritus. During peak spring flows, the river tends to shift its bed sediments

and cut new channels. The magnitude and extent of erosion are dependent upon many factors identified in this study. However, major shifts in channel alignment must be attributed to high velocity flows during periods of flooding. Prior to 1947, the river followed a relatively consistent path through the valley. From the beginning of the period of record, 1930 to 1946, peak spring flow averages were considerably lower than those during subsequent years. For at least 16 years a combination of drought and gradual spring snow melt created the illusion that the Bitterroot River was a stable, meandering stream. The absence of high peak spring flows allowed the river to maintain a relatively consistent course and stable channel. The significant flood events of 1947 and 1948 were the turning point. Two major flood years occurred again in 1972 and 1974. Bank stability has also been aggravated by the composite effects of various human activities including: (1) river bank alteration, (2) floodplain development, (3) logging methods and road construction, (4) irrigation diversions and practices, and (5) range management and grazing practices. The "Sleeping Child" fire in 1961 also contributed an adverse impact on channel stability.

The Bitterroot River is an inherently dynamic river, and many of the problems concerning channel stability are not man-induced. However, a variety of actions may be employed to reduce damage and encourage stability. Recommended approaches include: (1) construction of temporary structures, (2) education of local residents concerning the behavior of the river, (3) cooperation of contingent landowners in adopting consistent management practices, (4) limitation of activities in the floodplain, and (5) increased use of groundwater pumping for irrigation. It is essential to recognize the potential responses of the river to activities on the watershed. The river's behavior should be respected, and human interference should be limited and

carefully planned. Impacts to both upstream and downstream reaches must be considered before altering a channel section or building any type of structure in or near the river.

I. OBJECTIVES OF THE STUDY

The primary objective of this study is to investigate the causes of channel instability and to suggest methods of enhancing the stability of the Bitterroot River, particularly in the reach between Hamilton and Stevensville. The river flows over coarse alluvium composed largely of gravels, cobbles, and sands, with banks composed of finer materials. During high flows, the river creates new channels and new deposits. The erosive energy of the water cuts into the channel banks, creating localized erosion and causing portions of the bank to randomly slough into the river.

Besides losing valuable property, lateral migration of the channel results in problems with irrigation headgates. When the main channel shifts, water diversion structures may no longer be able to access water, particularly during periods of low flow. Bridges have been left to span dry land as the river sought a new path through the valley. The instability of the Bitterroot River results in channel splitting, lateral migration, bank erosion, localized scouring and deposition, and flooding. The magnitude of these processes is greatest during high flows. The purpose of this investigation is to identify possible causes of channel instability in the Bitterroot River and to suggest alternatives for reducing this instability.

II. VIEWING THE STUDY AREA

2.1 Aerial Reconnaissance

Dr. D. B. Simons, Mr. J. D. Schall, and Ms. S. S. Ellis of the project team from Simons, Li & Associates, Inc. (SLA) visited the study area to conduct personal observations of the Bitterroot River channel. Mr. Chris Hunter of the Montana State Department of Natural Resources and Conservation (DNRC) arranged for a flight to observe the river from Missoula south, to a point several miles up the west fork. The following account describes observations made during the flight.

From the air it was apparent that the river had historically worked back and forth across the floodplain as it flowed from the present-day sites of Hamilton to Lolo. Between Hamilton and Florence, the river exhibits a braided, unstable nature. (According to Simons and Senturk (1977) a braided river is defined as generally wide with poorly defined and unstable banks and is characterized by a steep, shallow course with multiple channel divisions around alluvial islands).

Considerable amounts of riprap have been placed along sections of the bank. The many channel bars piled with large quantities of debris indicate the instability and dynamics of the system at flood stage.

Other observations included: a new home being constructed in a very dangerous location near the river, and gravel pits in operation along the river in the vicinity of Corvallis.

Above Corvallis the Army Corps of Engineers has straightened a channel section to some extent and revetted the bank with riprap. Riprap has been placed both upstream and downstream of Woodside Crossing near Corvallis. Mr. Peterson indicated where the river had shifted laterally from east to west since 1951.

Above Hamilton, the river takes on a much more stable appearance. The water is confined to a single channel, although over geologic time the channel has moved laterally to a limited extent. Here several large irrigation canals divert water from the river. These structures are relatively crude with no gates to control the inflow. Basically, they consist of sills that hold the water level high enough for water to flow into the canals. These diversions do not possess equipment to exclude the entrance of sediments into the canals. A complex system of ditches extends throughout the valley.

The Hamilton sewage treatment plant is located on the floodplain. This sewage can easily contaminate the river during periods of high flow.

The East Fork of the Bitterroot is confined to its channel and is a very different type of river than the Bitterroot River below Hamilton. Flying upstream from Hamilton, an obvious change was observed in the river's behavior. Here, it is incised, forming a deeper channel, creating a much more stable river. The particle size of the bed material becomes greater with increased upstream distance.

Southeast of Hamilton wildfire has burned extensive acreage in the higher elevations of the Sapphire Range. Fire exposes more of the watershed to the erosive action of water, increasing transport of sediments into the channel. In addition, large blocks of land have been clearcut and extensive road systems built on the mountain sides. Removal of the vegetative cover and disturbances to the land surface can affect the river system behavior both in terms of increased sediment load and slightly increased discharges.

The divide between the East Fork and West Fork contains heavily timbered slopes with little human disturbance. Downstream of the Painted Rocks Reservoir (a reservoir which lacks sufficient storage capacity to control flooding during spring runoff), a considerable number of timber clearcuts are visible. However, no tremendously active erosion sites were discernable.

No single source was identified that would produce the large quantities of sediment required to affect the geometry of the Bitterroot River.

An important aspect of this study is to determine the volume of sediments tributaries deliver to the river. The development of tributary bars would indicate a relatively large sediment input. However, the impression given from flying over the river implies this is not the case. It appears that most of the sediments carried to the river are relatively fine in nature compared to the river bed materials. These finer particles would tend to wash through the system--particularly during high flows in late spring. The bed itself appears to be composed of coarse sand, gravel, and cobbles, most of which were probably deposited during the past glacial history of the valley.

2.2 Floating the River

In order to obtain a better appreciation of problems concerning the Bitterroot River channel, the river was floated from Bell Crossing to the Stevensville Bridge. During the trip samples from the overbank area were gathered to allow later determination of the sizes of sediment entering the river as a result of bank erosion. Bed sediment samples were collected, as well as sediment found at the mouths of inflowing tributaries.

This reach of the river appears to be very dynamic and subject to rapid change during periods of high flow. Numerous large cottonwoods had fallen into the river with roots facing upstream, and still held soil. The trees that fall into the river, as well as the gravel bars within the channel, obstruct the flow and contribute to the constantly changing channel patterns.

At the location where Big Creek joins the Bitterroot River, the presence of small ripples of sand measuring about 15 inches from crest to crest and about 1 inch in height indicated that some sands are entering from Big Creek

even during lower flows, although very little silt is entering the main channel. The water is very clear with virtually no suspended material.

The north bank of Big Creek consists of riprap which continues downstream along the bank of the Bitterroot River. However, the river has moved away from this bank in recent years.

Extensive riprapping has been installed along the west bank downstream from the mouth of Big Creek. The largest riprap is about 3-4 feet in diameter. The river impinges against the riprap, eroding a pool at its base as the water flows along it. The eroded bed material then drops out downstream. Downstream of the riprapped bank, an increased amount of sand has deposited among the coarser material. These sediments drop out where the river widens and the water slows. The origin of the sand can be identified by its lighter color. This sand is largely related to the scour hole that has developed as the main current flows parallel to the riprap, gouging out a deeper hole or pool.

At a channel fed by springs and irrigation return flow that enters the river on the east bank, sediment appeared to be composed of fine material delivered by what will be termed "spring irrigation return flow #1."

A section of riprapping was observed jutting out into the water resulting from the river having eroded the bank behind it. Further downstream the river was rapidly eroding the bank encroaching a house overlooking the river.

Floating the river thus allowed pertinent observations to be made of its erratic and dynamic nature and has shown clear evidence of its instability.

2.3 Visiting Selected Sites

The west- and east-side tributaries were (also) inspected by driving to selected sites. On Bass Creek, a west-side tributary, large cobbles form the streambed, and the channel appears to be quite stable above the campground.

The channel is steep enough to carry any of the finer sediments into the Bitterroot River, however, such sediment contribution would be quite small. Near the Kootenai Creek trail the channel is extremely well-controlled by solid rock outcroppings and loose boulders. Again, any sediment entering Kootenai Creek would be transported down to or near the river since the gradient is steep. However, it appears that the quantities of sediment being discharged from the area have very little impact on the overall behavior and characteristics of the Bitterroot River.

The east-side of the valley has much less vegetative cover, consisting mainly of open grasslands at the lower elevations. The bed of the South Fork of Burnt Fork Creek was examined into the canyon area. It consists of relatively coarse material and rock outcroppings that prevent any significant downcutting. The channel appears to be quite stable. However, the drainage area itself is quite susceptible to erosion; and under severe storm events, relatively large quantities of fine sediments could be produced from the watershed. At Ambrose Creek, another east-side tributary, the watershed on the east side of the valley appears to be more susceptible to erosion, but even the bare hills are armored with coarser particles that protect the surface from erosion. This side of the valley gets considerably less precipitation than the west side, consequently the opportunity for erosion caused by rainfall runoff is limited. There was no evidence of rilling on the slopes, indicating that the land here is not a large source of sediment to the Bitterroot River.

Urban development on both sides of the Bitterroot Valley may result in more disturbance to the watershed, due to increased runoff from impervious surfaces. This growth has the potential to adversely effect the river, both in terms of channel stability and water quality.

III. EVALUATION OF THE BITTERROOT SYSTEM

3.1 Topography

The Bitterroot River lies in a wide valley bounded by the Sapphire Mountains to the east and the Bitterroot Range to the west and south. The river flows north to its confluence with the Clark Fork River at Missoula. The Sapphire Mountains are characterized by rounded profiles with maximum elevations of about 8,800 feet. The rugged Bitterroot Mountains are characterized by glacial features such as carved U-shaped canyons, cirques, sharp ridges, and glacial lakes.

The Bitterroot Range runs north/south with narrow, steep walled canyons cutting eastward towards the valley. Each canyon originates in a glacial cirque. The relief is rugged and much of the higher elevations consists of exposed granitic rock slabs, while the canyon bottoms are generally forested. The maximum elevation of 10,175 feet occurs at Trapper Peak, west of Conner. The valley elevation ranges from 3,832 feet near Darby to 3,273 feet near Florence. Between Darby and Florence, five major tributaries enter from the Sapphire Mountains and 20 from the Bitterroot Mountains.

3.2 Geology and Soils

The following description is a brief account of the geology of the Bitterroot Valley based on a study by McMurtrey (1972). A map of the geologic formations accompanies the description (Figure 1). Table 1 is an explanation of geologic deposits shown on the map of Figure 1.

PRE-CENOZOIC

A) Precambrian Rocks

Metamorphosed Precambrian rocks such as border-zone gneiss occur on the Bitterroot Mountain ridges and as local outcrops. Precambrian sedimentary rocks are also exposed along the margins of the Bitterroot

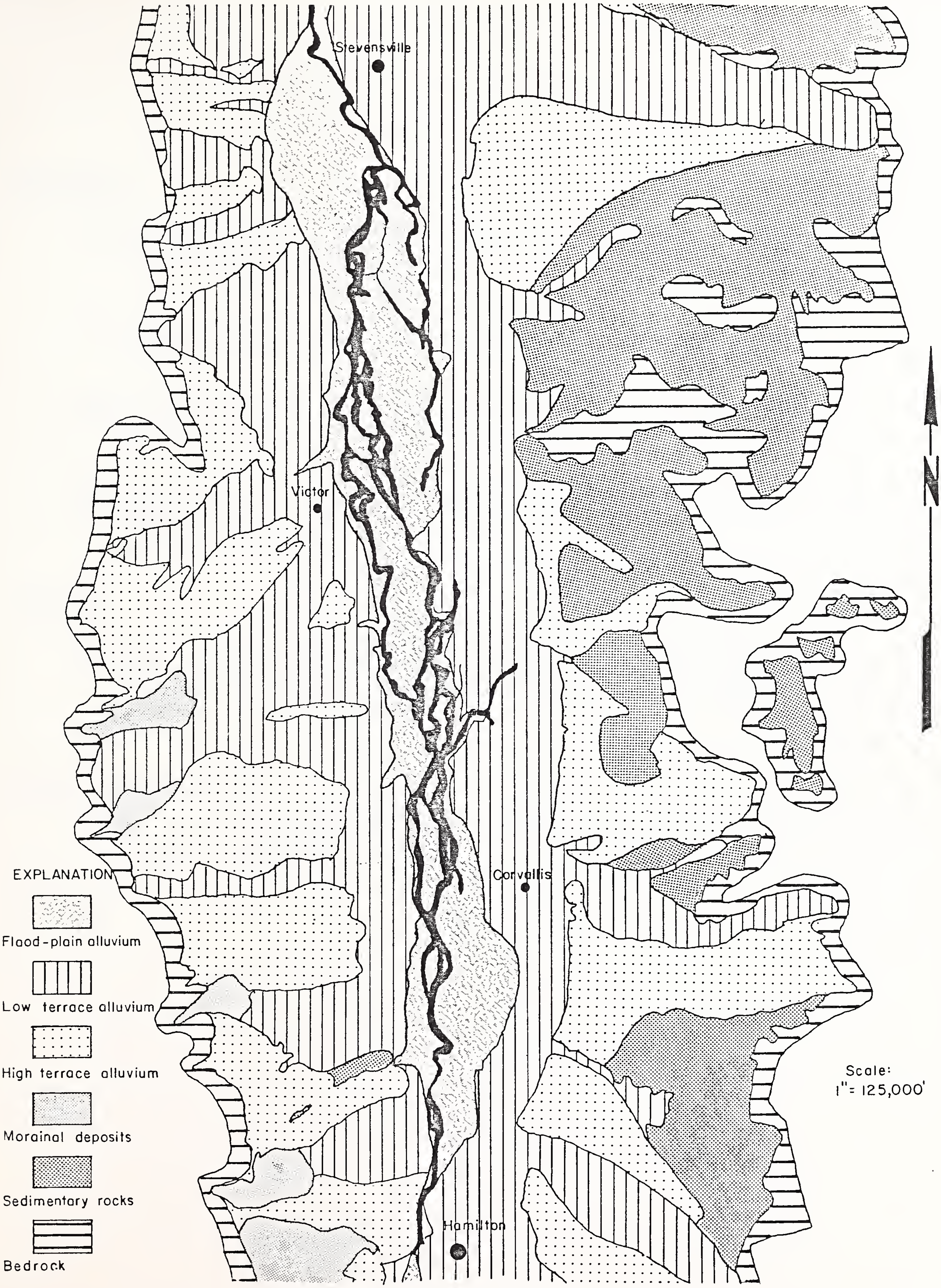


Figure 1. Geology of the Bitterroot Valley, Montana.

From: USGS Geologic Map

Table 1. Explanation of Geologic Deposits Shown on Map

QUARTERNARY

Floodplain alluvium: Unconsolidated sand, gravel, and silt beneath the floodplain of the Bitterroot River; includes reworked glacial drift and Tertiary sediments.

Low terrace alluvium: Unconsolidated sand, gravel, silt, and soil; includes glacial drift and reworked glacial drift and Tertiary sediments.

High terrace alluvium: Unconsolidated sand, gravel, some boulders and silt; includes glacial drift, reworked Tertiary sediments, and talus deposits.

Morainal deposits: Unconsolidated deposits of boulders, cobbles, gravel, sand, silt, and clay; occurs at the mouths of some west-side tributary canyons.

TERTIARY

Sedimentary rocks: Semiconsolidated bedded deposits of sand, silt, clay, ash and some gravel; these rocks probably underlie most of the valley, but are best exposed along high terrace remnants on the east side of the valley.

PRECAMBRIAN TO TERTIARY

Bedrock: Includes shale, quartzite, argillite and limestone of Precambrian age; granitic rocks of the Idaho Batholith; Tertiary volcanic rocks.

Valley. Rocks of the Ravalli Group are mainly quartzites and quartzitic argillites. Rocks of the Newland Limestone crop out over certain areas along the sides of the valley. These rocks are mostly argillaceous limestones and limey argillites. The Ravalli Group and the Newland Limestone are members of the Belt Supergroup and underlie much of the valley fill.

B) Mesozoic Rocks - Cretaceous Period

Cretaceous rocks border the Bitterroot Valley. The Bitterroot Mountain slopes are underlain by granitic rocks of the Idaho batholith that intruded about 100 million years ago. Masses of the Idaho batholith also occur in areas of the Sapphire Mountains. The Bitterroot Valley became a marginal trough during the intrusion of the batholith. A huge slab of border-zone gneiss and overlying Belt rocks were domed and have since been eroded from above the Idaho batholith.

CENOZOIC ERA

A) Tertiary Period

Tertiary volcanic rocks form a few local outcrops on high terraces near the mouths of some of the Bitterroot Mountain canyons. Faults along the eastern margin of the batholith may be related to intrusions by magma during the Tertiary Period. Most of the valley fill consists of unconsolidated to semiconsolidated Tertiary sedimentary rocks. Tertiary strata rest on a surface of high relief composed of Precambrian Belt rocks. The probable total thickness of unconsolidated Tertiary sediments is close to 2,000 feet near the center of the valley east of Florence. The Tertiary strata consist mainly of eroded material from the mountains, as well as volcanic ejecta. Coarse colluvial deposits along the base of the mountains grade valley-ward into fine-grained alluvial-

fan deposits. These deposits intergrade with floodplain deposits of silt and clay with lenses of channel sand and gravel. Extensive deposits of volcanic ash interbed with the Tertiary sediments. Tertiary colluvial outcrops on high terrace scarps consist of loose freshly weathered feldspar and quartz derived from the granitic Idaho batholith. Most of the exposed Tertiary floodplain deposits on the east side of the valley consist of semiconsolidated silt with lenses of bentonite clay. The Tertiary channel deposits are typically crossbedded and composed of well-rounded grains of quartz, and fragments of granite, border-zone gneiss, and argillaceous rocks. Fragment sizes range from rocks up to 10 inches in diameter near the mouths of tributary canyons to fine gravel and sand near the center of the valley. Toward the end of the Tertiary period, the ancestral Bitterroot River eroded a broad valley into the Tertiary sediments.

B) Quarternary Period

Rapid erosion occurred during the beginning of the Quarternary Period. Glacial debris accumulated on the west border of the valley, and stream deposits on the east. During the height of Pleistocene glaciation, the Clark Fork River was ponded by masses of the Cordilleran ice sheets, while the Bitterroot Valley was innundated by glacial Lake Missoula which existed as recently as 6,000 years ago. As the lake drained, wave-cut benches were formed during periods of temporary stability. Following the drainage of the lake, large outwash fans were deposited on the tributary floodplains. During a mid-Pleistocene interlacustrine interval, the Bitterroot River and its tributaries eroded into the early Pleistocene alluvium and Tertiary fill. Deep V-shaped canyons were eroded into the lower courses of the U-shaped glacial canyons on the west side of the valley.

Quarternary alluvium averages about 40 feet thick over much of the valley. This alluvium consists of stream-transported detritus from the Bitterroot Mountains, and reworked Tertiary material. The alluvium was deposited in rapidly changing fluvial, glaciofluvial and glaciolacustrine environments. The various sedimentary deposits interfinger and intergrade both laterally and vertically. Sorting increases and grain size decreases towards the valley center.

The Bitterroot River and its tributaries have cut below the level of the high terraces and partly drained the alluvium. High yield wells tap depressions in the surface of Tertiary sediments where the saturated zone of the overlying alluvium is thicker than average. Irrigation recharges the alluvium and prevents it from becoming completely drained.

Glaciofluvial deposits occur as outwash fans of angular to well-rounded fragments of granite and border-zone gneiss. Size varies from silt to boulders of more than 20 feet in diameter. Water-bearing characteristics vary greatly within short distances because of the wide range in grain size and the occurrence of lateral lensing. In general, sorting and permeability are lowest near the base of the mountains and highest towards the valley center.

3.3 Climate and Precipitation

The Bitterroot Valley has an average annual temperature of about 45°F, with an average monthly high of 66°F in July and an average monthly low of 23°F in January measured at Stevensville. Thirty to forty percent of the annual precipitation falls as snow at the lower elevations. Above 7,000 feet, more than 70 percent of the precipitation is snow. However, at the higher elevations of the Bitterroot Mountains, as much as 85 percent may be

in the form of snow. The average frost-free period is 99 days in Darby and 122 days in Hamilton.

Average annual precipitation in the valley ranges from 18 inches in the upper valley to 12 inches near Florence. In the valley, the majority of the precipitation arrives in May and June, and dry periods occur from mid-July through August. Snowmelt from the mountains together with spring rainstorms, create peak flows in late May and early June. From late October through early May, snow accumulates in the Bitterroot Mountains, which receive most of their moisture in December and January. There is a marked increase in annual precipitation with increased elevation. Average annual precipitation is as high as 100 inches along the divide of the Bitterroot Mountains, and up to 50 inches along the sapphire Mountain Divide.

Total annual precipitation at Missoula is shown for 1930 through 1978 (Figure 2). This data can be used to identify relative wet and dry periods. From 1929 through 1940, the area experienced a drought with a mean annual precipitation of only 11.4 inches. For the period from 1941 to 1978, this value increased to 13.2 inches. However, the three year period from 1944 through 1946 was also exceptionally dry with a mean annual precipitation of only 10.9 inches.

April 1 snowpack expressed as equivalent water inches is presented for the years 1937-1978 (Figure 3). These measurements were taken at Lolo Pass, Idaho and can be used as a relative index to snowmelt contributions in different years. Snowpack was exceptionally low in 1940, 1941, 1942, 1944 and 1945. A series of years with low snowpack can result in lower peak flows in the Bitterroot River, creating temporary constancy in the river's course. Average April 1 snowpack increased from 28 inches for 1937 through 1946 to 34 inches for the period from 1947 through 1980. Timing of the snowmelt is more critical in producing floods than is snowpack along. High snowpack does not necessarily

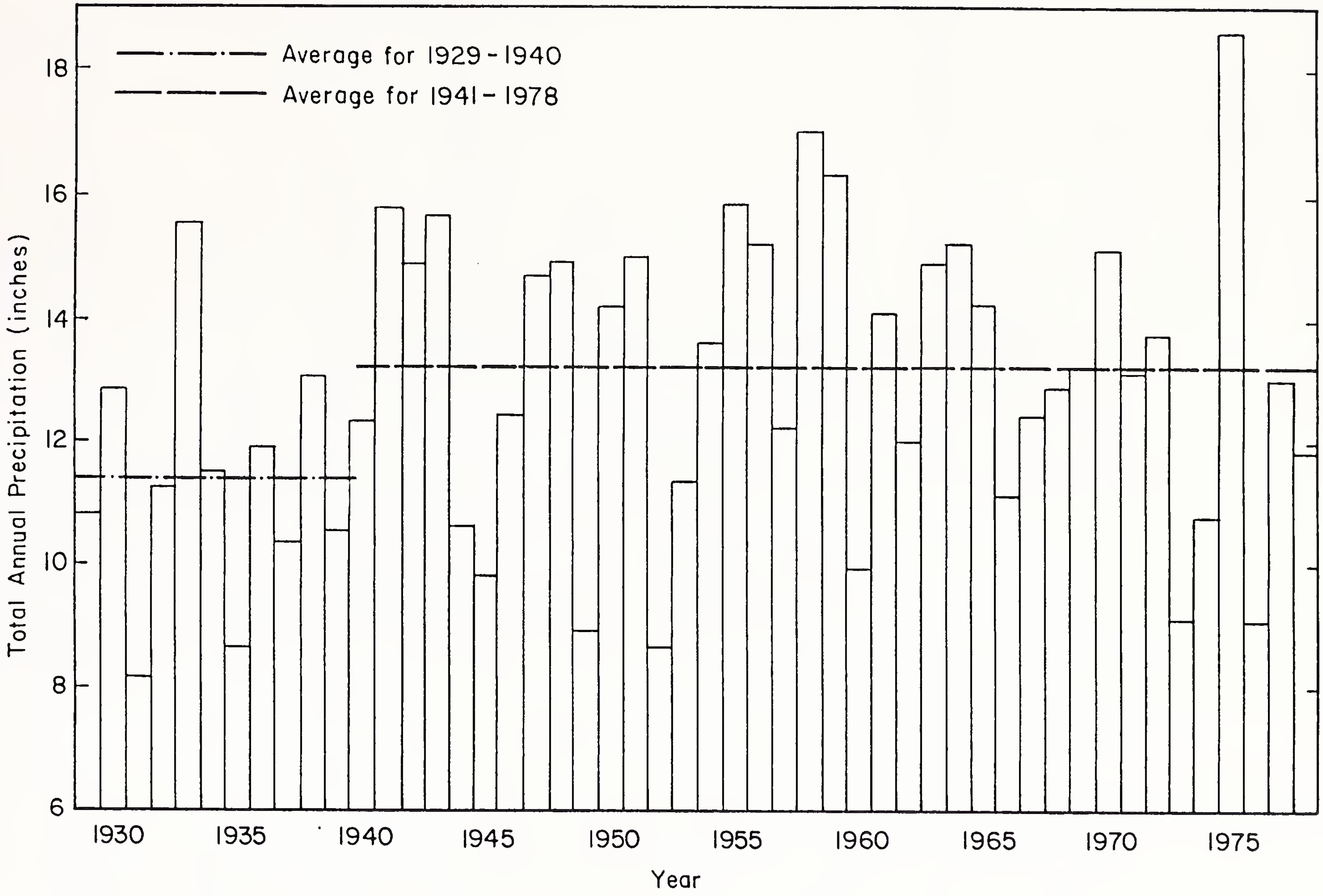


Figure 2. Annual Precipitation at Missoula, Montana: 1929:1978

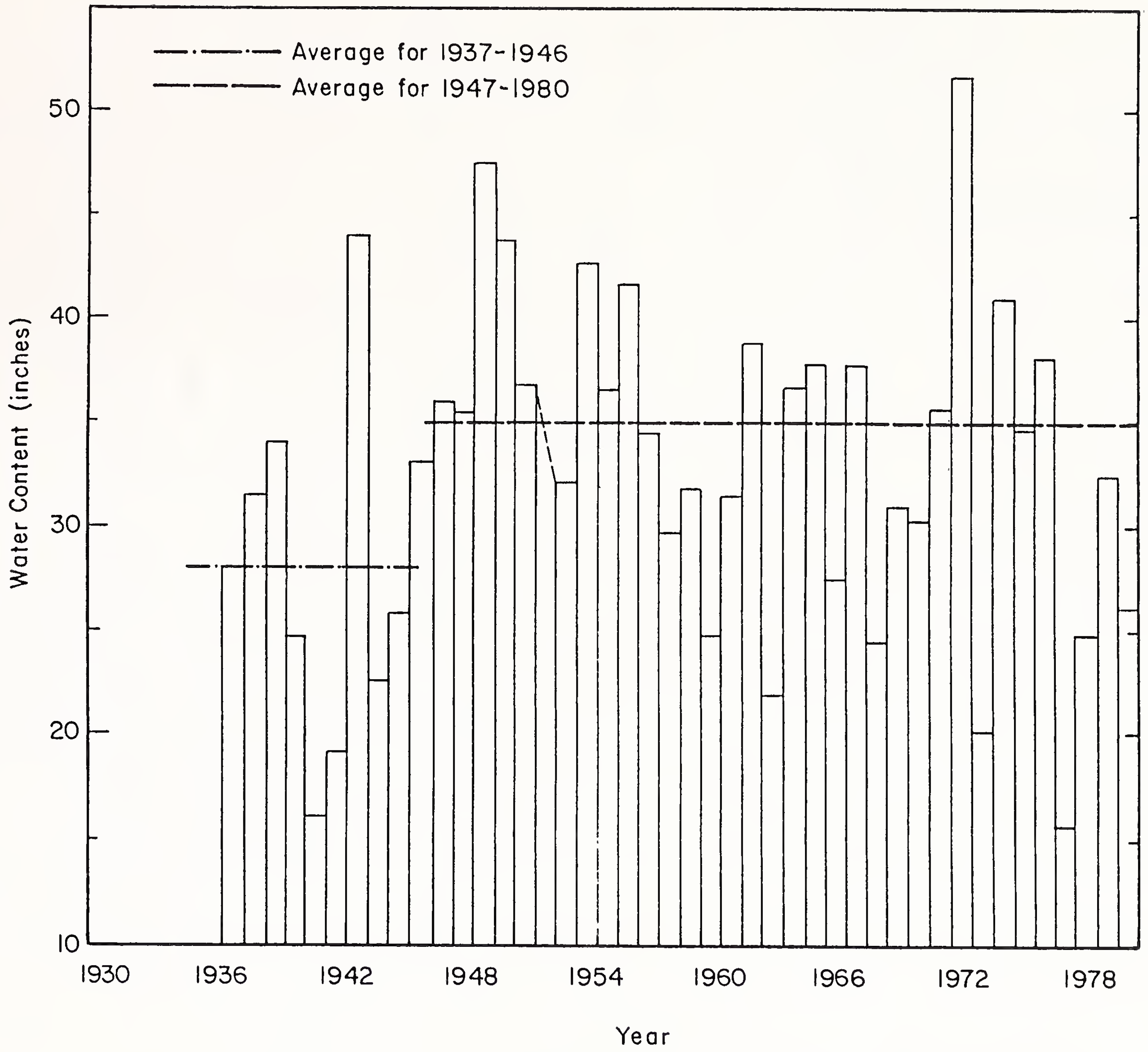


Figure 3. April 1 Snowpack at Lolo Pass, Idaho: 1937-1980

create high peak flows. If air temperatures during the spring allow the pack to melt gradually, flooding is less likely. However, if cold temperatures persist until late in the spring and then a series of much warmer days occurs, sudden rapid melting of a deep snowpack will create flooding. Also, if rainfall coincides with snowmelt the likelihood of flooding increases.

In section 3.4, annual maximum spring flow at two locations on the Bitterroot River is examined for the period of record. These records indicate a distinct correlation between April 1 snowpack and peak flow. The year 1943, however, is an exception. A deep April 1 snowpack did not result in exceptionally high peak flows in the Bitterroot River because the pack melted gradually throughout the spring. In fact, the water equivalent decreased from 44.3 inches to 33.6 inches during the month of April. For some years, records may be deceptive as April snows increased the snowpack.

3.4 Hydrology

3.4.1 Water Budget

The average annual water budget for the Bitterroot River drainage is shown in Figure 4 (Senger, 1975). The volume of 5,700,000 acre-feet represents the amount of water arriving as precipitation through the entire drainage area. About 64 percent of this precipitation is taken up by plants, or evaporates, never reaching the Bitterroot River. Approximately 2,100,000 acre-feet does enter the valley bottom-lands. This volume consists of contributions from the East Fork, West Fork and all tributaries below the forks, as well as precipitation falling directly into the valley bottom. About 29 percent of this water is diverted for agricultural irrigation. About one third of the water diverted re-enters the river as irrigation return flow. Annual groundwater discharge from domestic, municipal, and irrigation wells is estimated to be 160,000 acre-feet. The river returns this volume

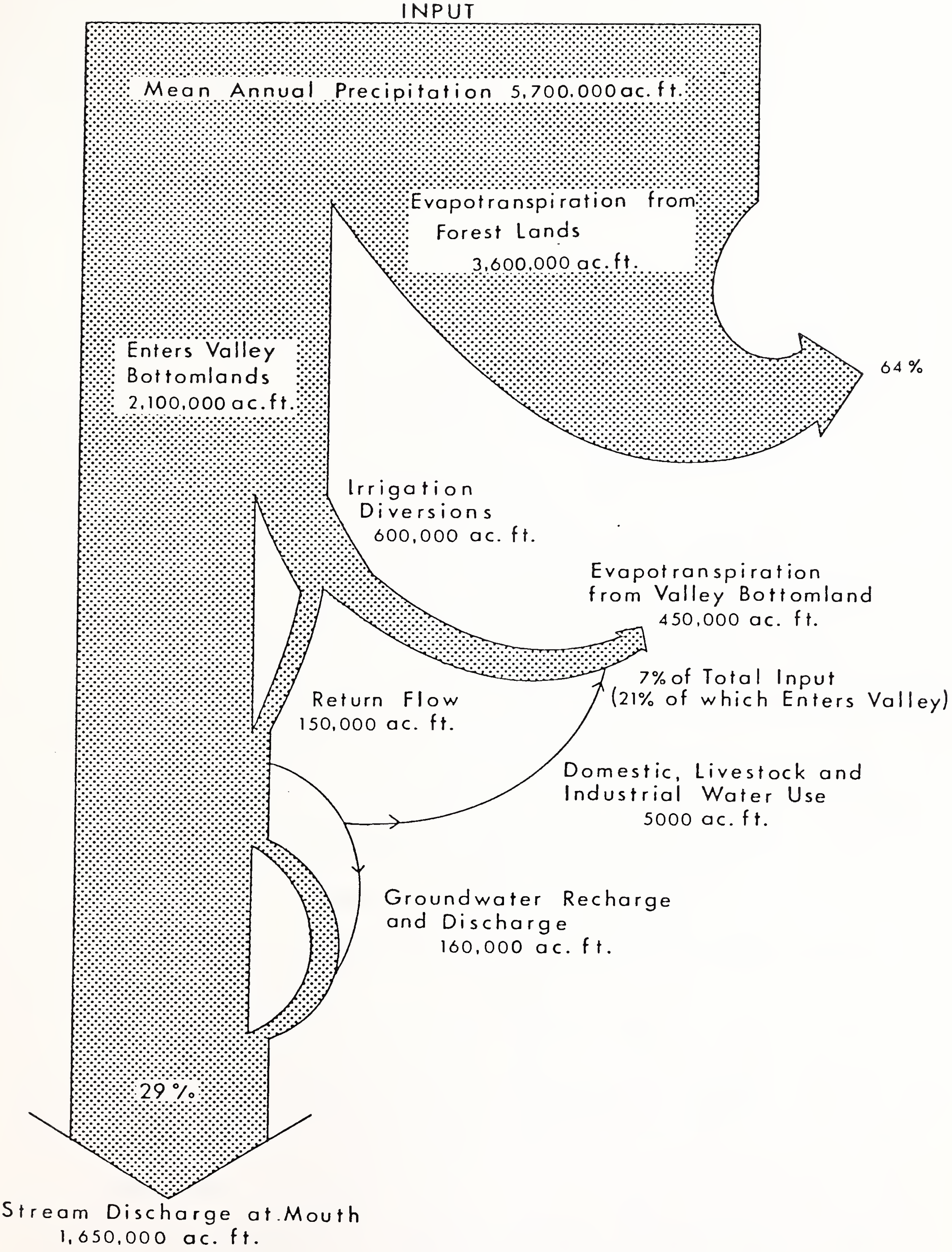

INPUT
Mean Annual Precipitation 5,700,000 ac. ft.
Evapotranspiration from Forest Lands 3,600,000 ac. ft.
64 %
Enters Valley Bottomlands 2,100,000 ac. ft.
Irrigation Diversions 600,000 ac. ft.
Evapotranspiration from Valley Bottomland 450,000 ac. ft.
7% of Total Input (21% of which Enters Valley)
Return Flow 150,000 ac. ft.
Domestic, Livestock and Industrial Water Use 5000 ac. ft.
Groundwater Recharge and Discharge 160,000 ac. ft.
29 %
Stream Discharge at Mouth 1,650,000 ac. ft.

Figure 4. Annual Average Water Budget:
Bitterroot River Drainage
From: Senger, 1975

to the ground water reservoir during high streamflow in the spring. On an annual basis, about 80 percent of the water initially entering the Bitterroot River is discharged at its confluence with the Clark Fork River. It is important to realize that this water budget is based on average conditions and represents inflows and outflows over an entire year.

3.4.2 Groundwater

Water-bearing capacities of geologic deposits in the Bitterroot Valley are presented in Table 2 (McMurtrey et al, 1972). Early Tertiary volcanics, Cretaceous intrusives and metamorphics, and Precambrian sediments have similar aquifer properties. In general, these rocks are dense and yield water only from fractures. The Newland Limestone transmits water through solution cavities, while the other rock types, mentioned above, store small volumes of water in fractures. Well yields soon diminish unless the fractures are recharged by the seepage from overlying strata. Few wells have been drilled into Tertiary sediments, thus little is known of their hydrologic properties. Studies of outcrops reveal that the colluvium along the mountain fronts is poorly sorted and unlikely to yield much water. The fine-grained alluvial fan deposits and flood-plain deposits are relatively impermeable and act as confining beds. Channel deposits of the ancestral Bitterroot River are permeable, yet these sand and gravel lenses are thin, yielding only small quantities of water (McMurtrey et al, 1972).

The floodplain of the Bitterroot River is formed on about 40 feet of Quarternary alluvium consisting mainly of well-rounded cobbles, gravels, and sands. This alluvium is hydraulically connected with the streams and is a good aquifer with high permeability and large storage capacity. Wells constructed in the floodplain are generally capable of supplying more than 250 gallons per minute (gpm). Near Corvallis, permeability of the aquifer is

Table 2. Water-bearing Properties of Rocks in the Bitterroot Valley

From: McMurtrey et al, 1972

System	Series	Formation	Description	Water-bearing Properties
Quaternary	Holocene	Alluvium	Stream-deposited clay, silt, sand, gravel and boulders reworked from older Cenozoic deposits	Alluvium is the most productive aquifer in area; yield of wells is somewhat variable but adequate for domestic and stock needs; along the Bitterroot River the yield is sufficient for irrigation, municipal or industrial wells.
	Pleistocene	Glaciofluvial glaciolacustrine, talus and fan deposits	Unsorted morainal and talus deposits ranging in size from clay to boulders; and stratified to poorly stratified glaciofluvial, glaciolacustrine, and fan deposits	Yields of wells are generally adequate for domestic and stock needs but vary with degree of sorting and thickness of water-bearing zones.
Tertiary		Colluvium	Poorly sorted coarse angular sand and gravel.	Not known to yield water to wells.
		Flood-plain and channel deposits	Silt and clay flood-plain deposits, and sand and gravel channel deposits, tuffaceous in places.	Yields small supplies adequate for stock and domestic wells from saturated channel sand and gravel. Fine-grained deposits are not known to yield water to wells.
Pre-Tertiary		Undifferentiated Precambrian & Cretaceous rocks	Dense, relatively impermeable sedimentary, metamorphic, and igneous rocks marginal to and underlying the Bitterroot Valley.	Small supplies yielded to wells from joints and from weathered surfacial material.

greater than average, and some wells yield more than 1,000 gpm. Wells into the alluvium of the low terraces and along the tributary streams generally yield less than 250 gpm.

Specific capacities of wells on the east side of the Bitterroot River range from 8 to 230 gpm per foot of drawdown. Wells on the west side range from 7 to 55 gpm, averaging about 20 gpm (McMurtrey et al, 1972). Groundwater recharge occurs during the spring as streamflow infiltrates into the aquifer. Since the groundwater reservoir is usually filled to capacity by June, much of the high spring runoff is rejected. Increased pumping of groundwater during the summer would lower the water table so that more stream flow could enter the aquifer during the following spring. Thus, groundwater pumping could reduce the volume of water leaving the Bitterroot Valley.

3.4.3 Stream Flow

Considering the water discharge, several aspects are important in the evaluation of river bank stability. In general, a channel achieves a pseudo-equilibrium over time so that during periods of low flow there is little erosion, and the channel and segments of the banks may even experience accretion. During periods of intermediate river flows some bank erosion and some deposition occur. In this range of flows, the dynamic processes that form rivers are apparent. With major flood events, major bank erosion occurs. Numerous experienced engineers and geologists have concluded that in most systems 90 to 99 percent of all significant bank erosion occurs during major flood events. In analyzing flow conditions in channels, it is obvious that the magnitude of the discharge in a given river system is an important factor affecting bank stability.

By analyzing runoff trends, events that aggravate channel stability may be identified. Runoff is described by total annual runoff, mean monthly

flows, flow durations, and flood frequencies. Peak flows of record provide estimates of extreme events, allowing calculations of recurrence intervals for flows of specific magnitudes.

The return period or recurrence interval for a flow is defined as the length of time during which a given flood level is expected to be equalled or exceeded just once. The 10-, 50-, 100-, and 500-year floods have a 10, 2, 1 and 0.2 percent chance, respectively, of being equalled or exceeded during any year. The recurrence interval represents the long-term average period between floods of a specific magnitude, but rare floods can occur at short intervals. Figure 5 illustrates flood levels for 4 different return periods as they increase in the downstream direction. For example, the 500-year flood at Hamilton is about 30,000 cubic feet per second (cfs), while the 500-year flood at Florence is about 40,000 cfs (Figure 5). A map showing major tributaries in the watershed is presented in Figure 6. Located on the map are selected gaging stations along the Bitterroot River and its tributaries. Table 3 summarizes flows recorded at these stations, listing mean annual flows and the range of recorded flows, as well as drainage basin area.

BITTERROOT RIVER STREAM FLOW

Mean monthly flows are illustrated for the West Fork, East Fork and the Bitterroot River at Darby (Figures 7, 8 and 9). These hydrographs are based on flow data at map locations 1, 2, and 3, respectively (Figure 6). Peak flows occur in May and June as a result of snowmelt. Five-year moving averages for annual runoff at the Darby station are shown in Figure 10, while peak flows and low flows are given in Figures 11 and 12. These graphs illustrate that from 1934 through 1946, both total annual runoff and peak spring flows were substantially lower than in following years. The annual peak flow for 1937 through 1946 averaged only 4,300 cfs, while for the years 1947

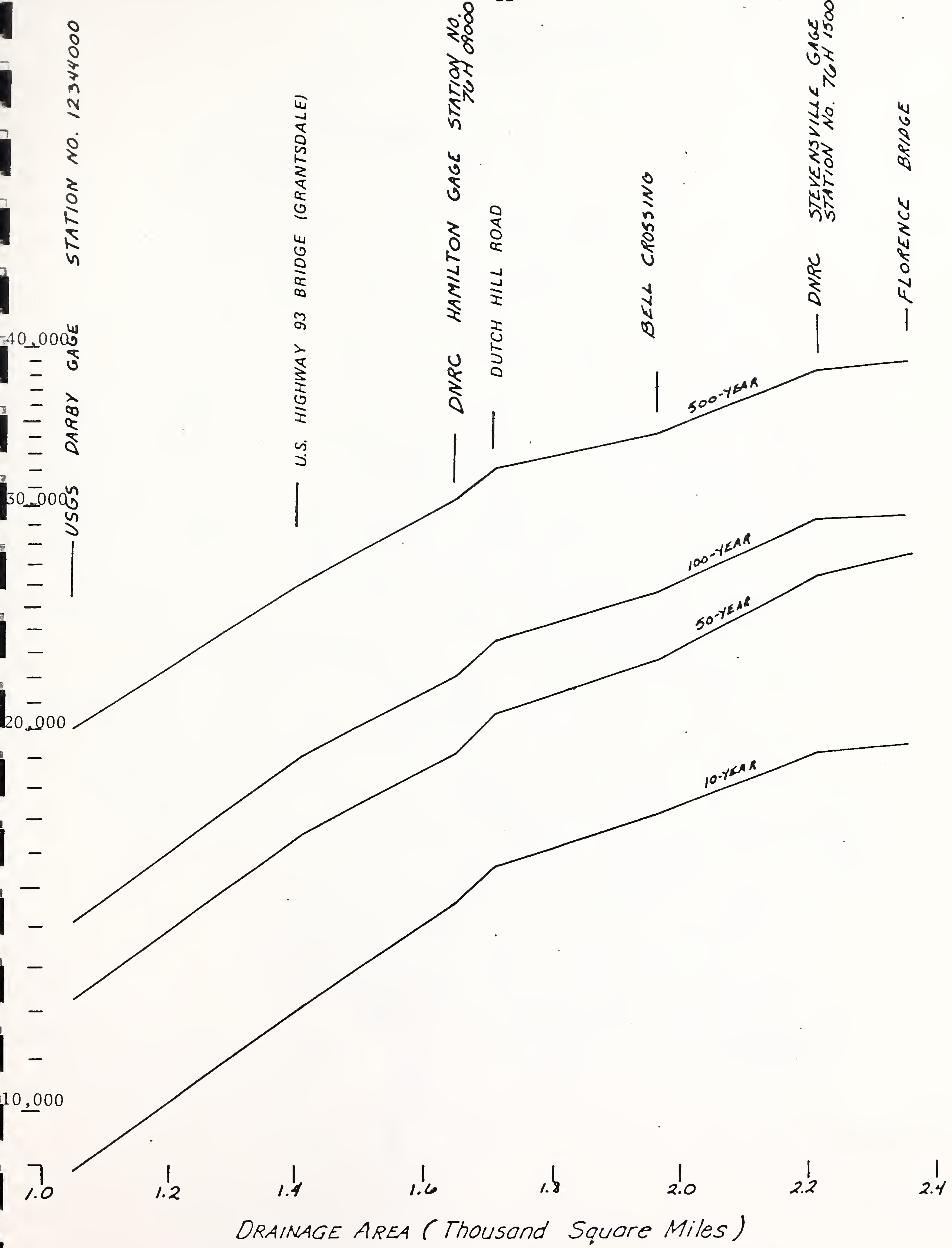


Figure 5. Bitterroot Drainage Area as Compared to Discharge.
From: FEMA, 1980

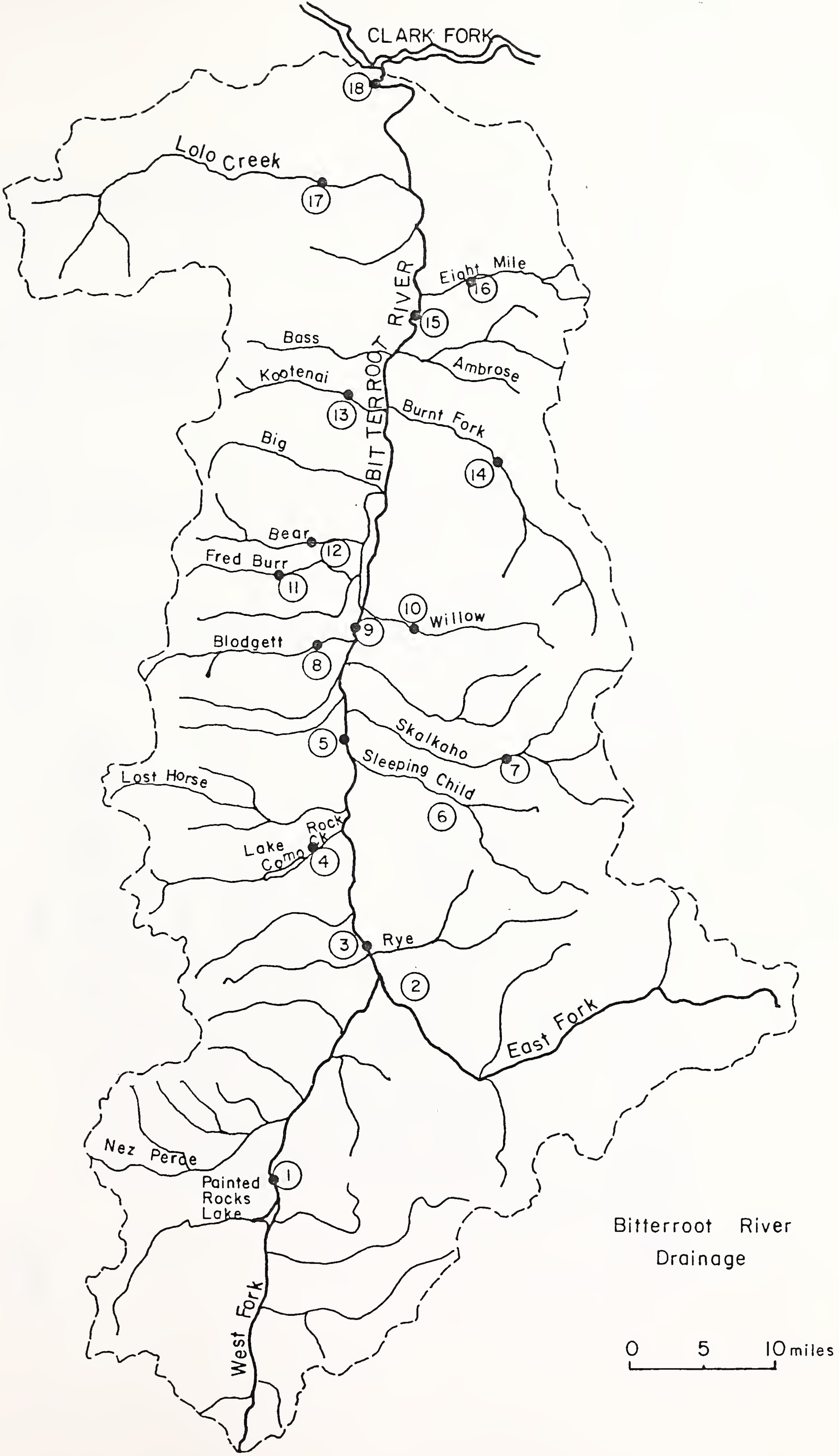


Figure 6. Major Tributaries and Selected Gaging Sites.

Table 3. Flows at Selected Stations in the Bitterroot Drainage

Map Location	Station Name	Drainage Area (mi^2)	Mean Annual Flow (cfs)	Maximum Recorded Peak (cfs)	Minimum Recorded Flow (cfs)
1	West Fork Bitterroot River Near Conner	317	288	4060	0.2
2	East Fork Bitterroot River Near Conner	381	279	3270	1.4
3	Bitterroot River Near Darby	1049	918	11500	71.0
4	Rock Creek Near Darby	55	149	1580	0.0
5	Bitterroot River Near Grantsdale	1414	1500	12900	5.0
6	Sleeping Child Creek	63	--	305	11.0
7	Skalkaho Creek Near Hamilton	88	93	1210	10.0
8	Blodgett Creek Near Corvallis	26	70	836	1.2
9	Bitterroot River Near Corvallis	1711	--	12800	112.0
10	Willow Creek Near Corvallis	22	15	168	1.0
11	Fred Burr Creek Near Victor	26	52	23100*	2.7
12	Bear Creek	27	66	1340	0.6
13	Kootenai Creek	29	79	1300	2.0
14	Burnt Fork Creek	74	48	720	2.0
15	Bitterroot River Near Florence	2354	2173	20300	365.0
16	Eightmile Creek Near Florence	21	7	104	1.0
17	Lolo Creek	250	215	2500	6.3
18	Bitterroot River Near Missoula	2844	2289**	38300	370.0

From: Senger 1975 and USGW Water Supply Papers

* Dam failure

** Difference between flows in Clark Fork above and below Missoula corrected for Rattlesnake Creek inflow

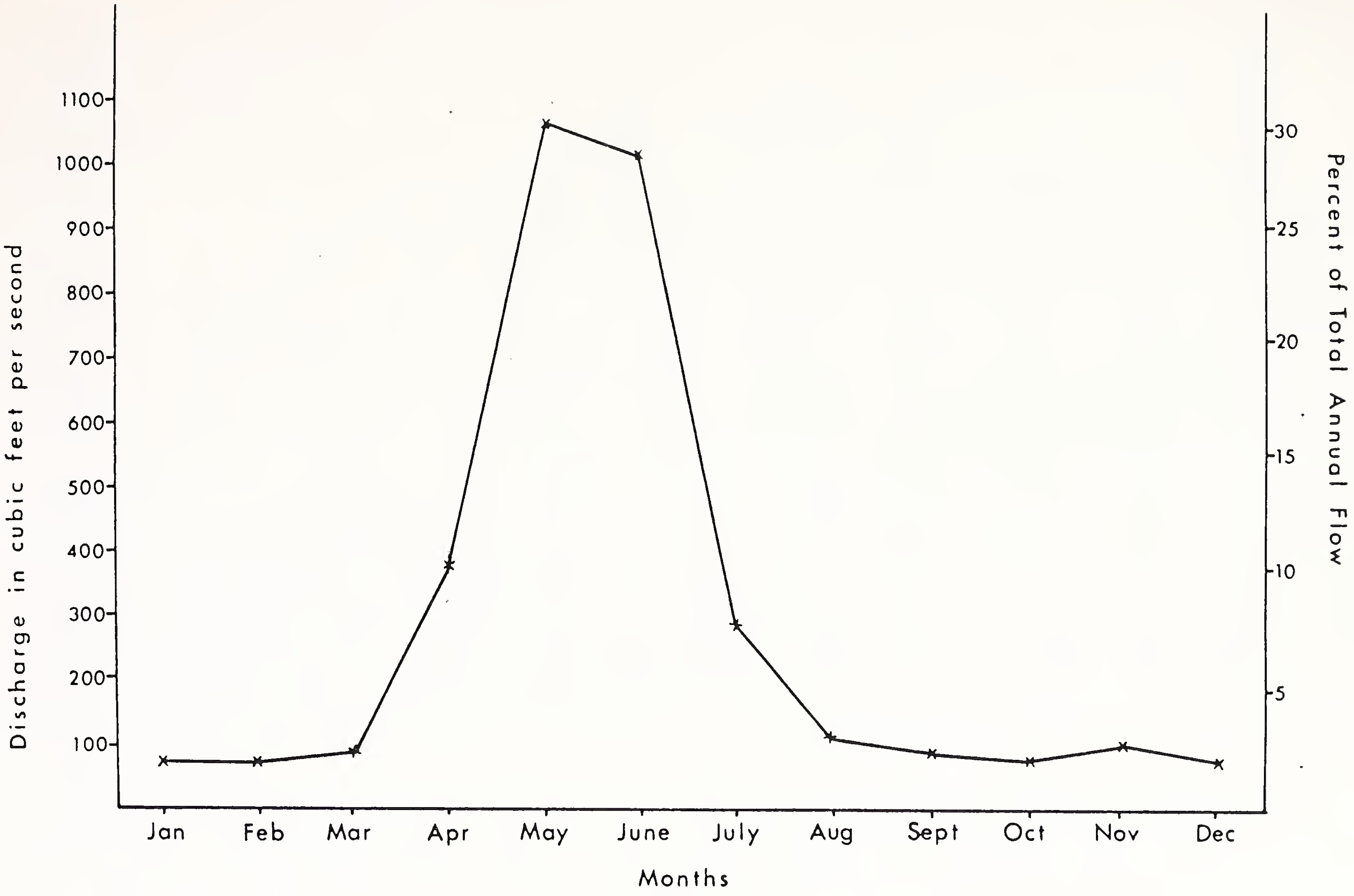


Figure 7. Mean Monthly Flows for the West Fork Near Conner
From: Senger, 1975

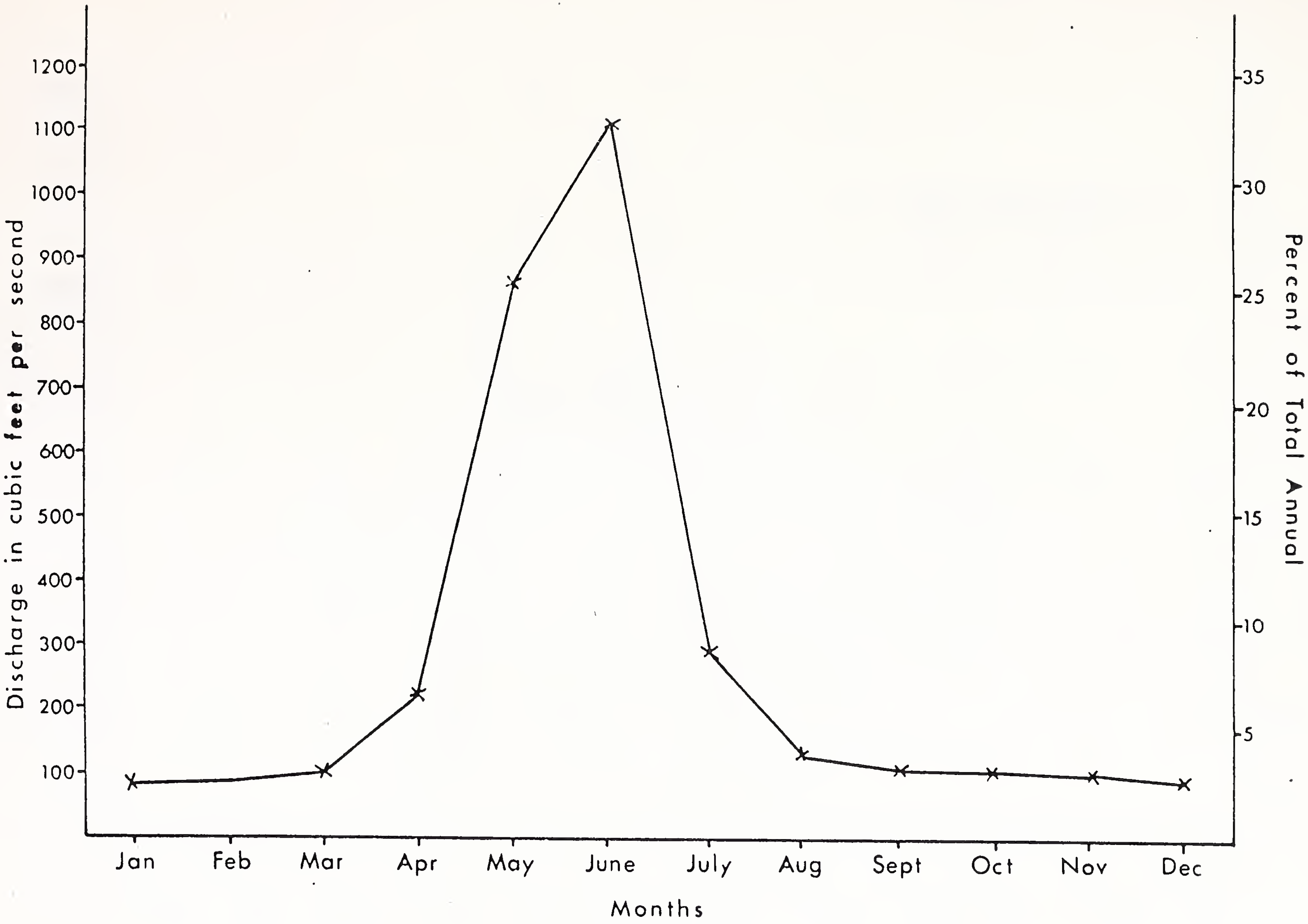


Figure 8. Mean Monthly Flows for the East Fork Near Conner
From: Senger, 1975

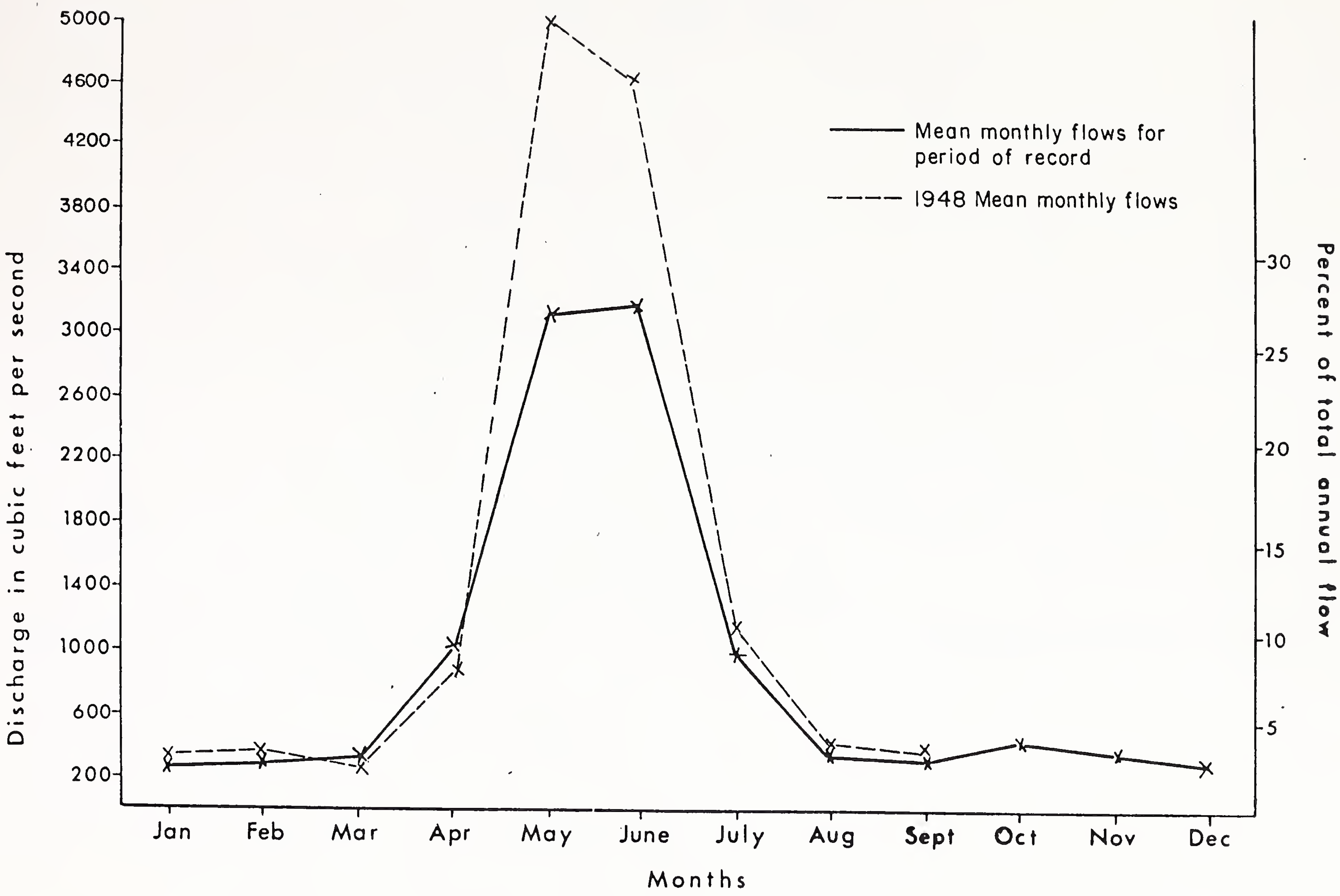


Figure 9. Mean Monthly Flows for Bitterroot River Near Darby Modified from Senger 1975.

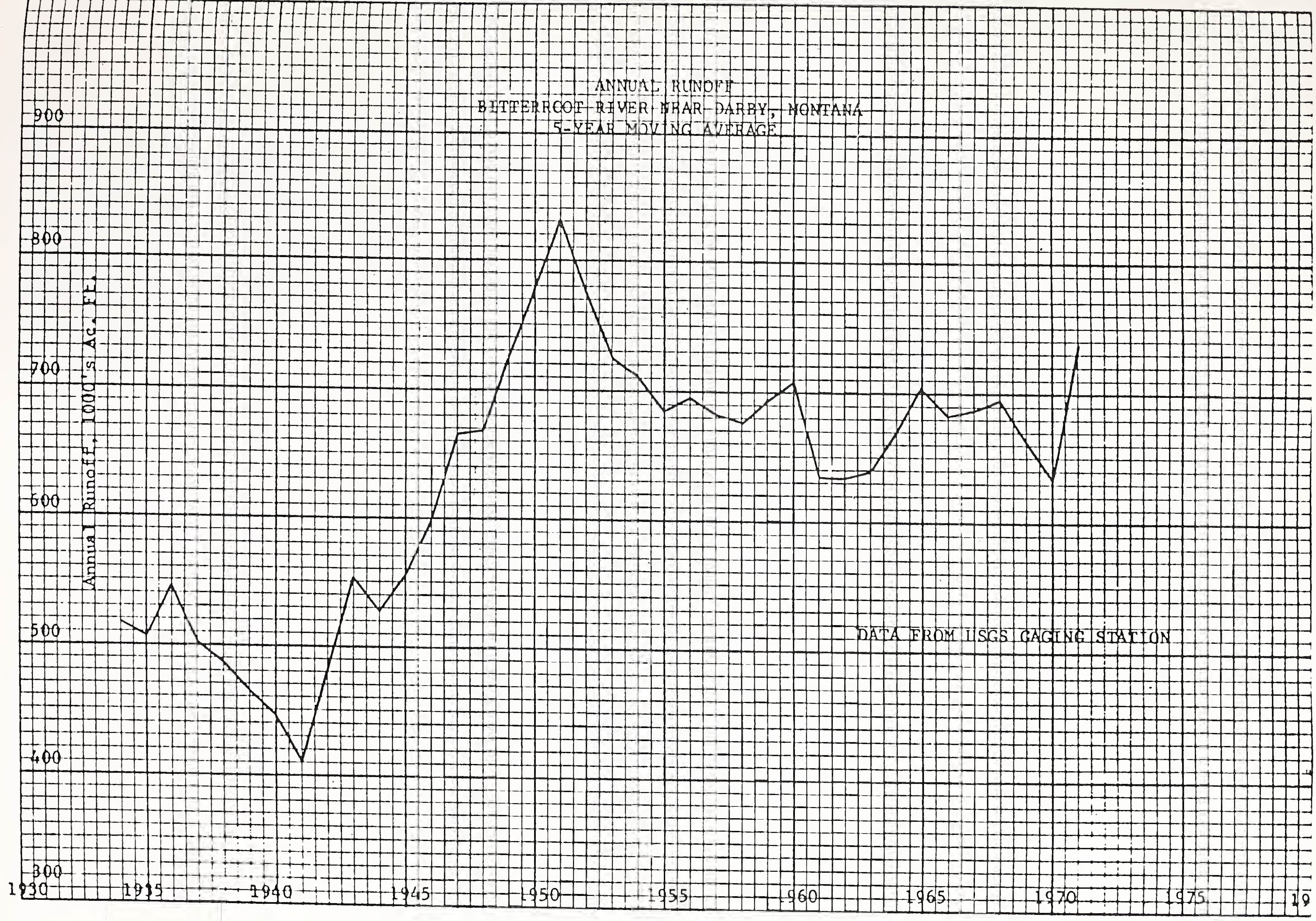


Figure 10. Runoff trends on the Bitterroot River drainage.
From: Farnes and Shafer, 1972

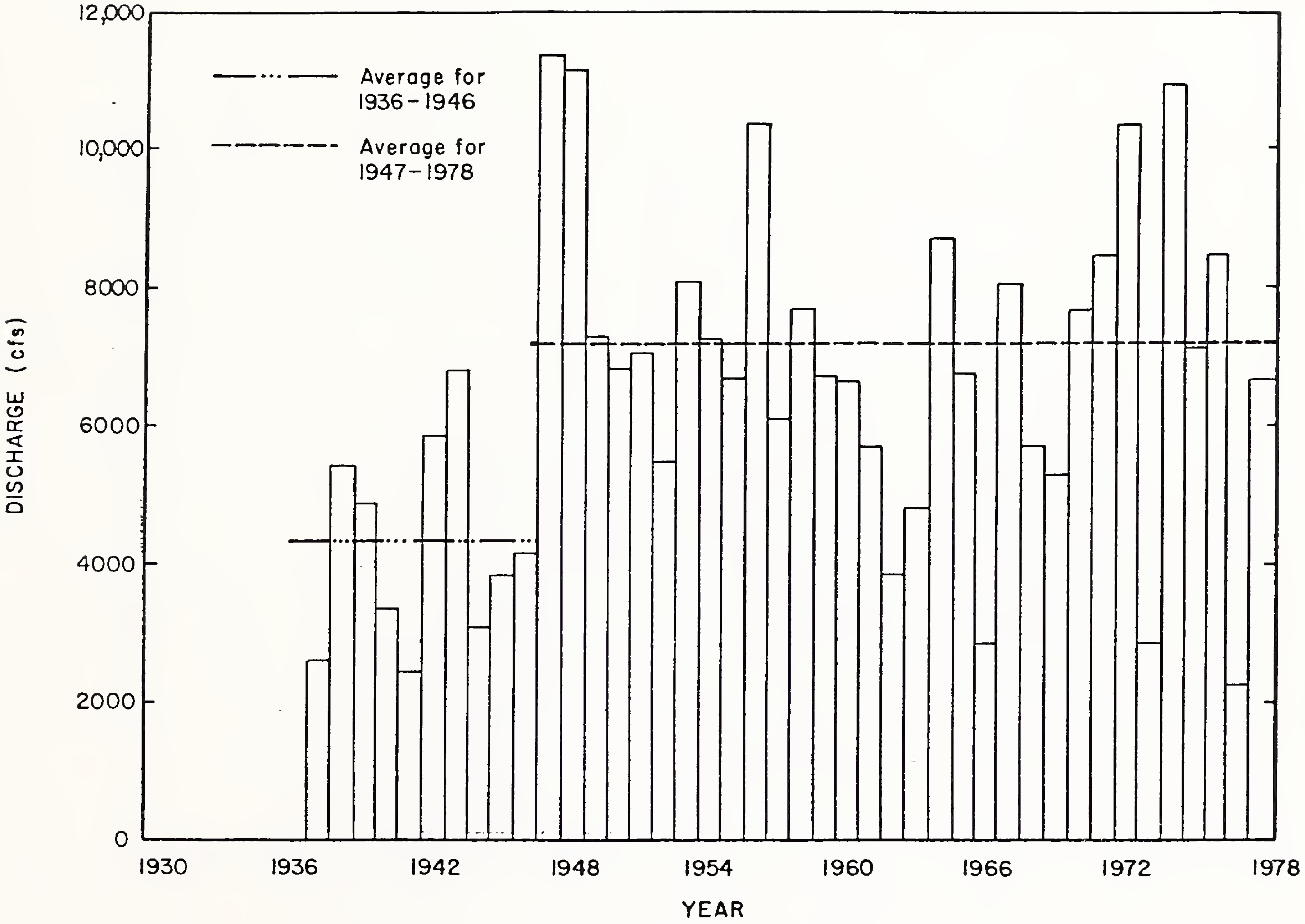


Figure 11. Peak Flows: Bitterroot River Near Darby: 1937-1978

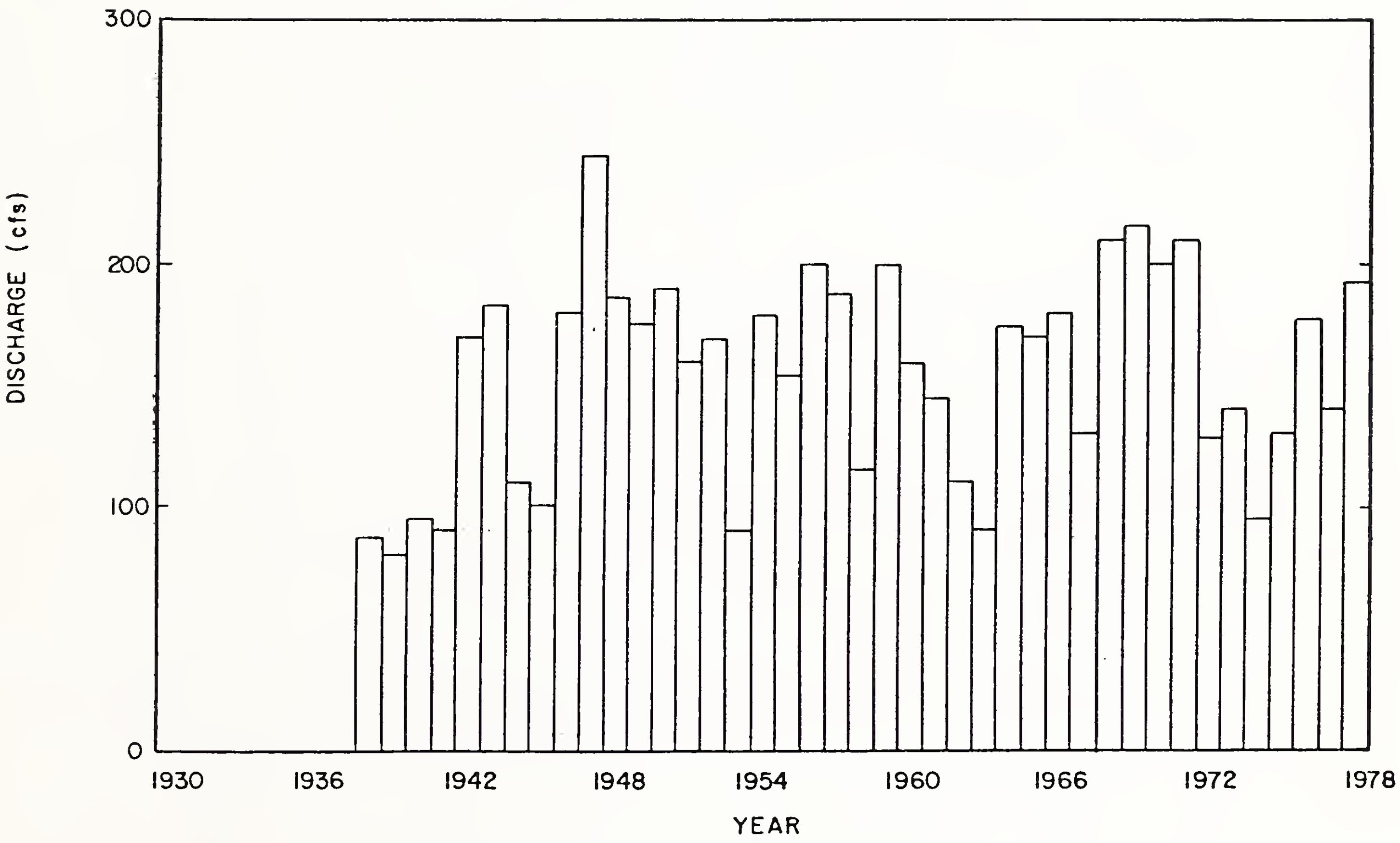


Figure 12. Lowest Flows: Bitterroot River Near Darby: 1937-1978

through 1978, it averaged 7,100 cfs. Figure 13 shows recurrence intervals for flows of specific magnitude at the Darby gaging station. The 1947 and 1948 peak flows of 11,500 and 11,300, respectively, can be found on the flood frequency graph to correspond approximately to a 35-year recurrence interval. The occurrence of two large floods in consecutive years undoubtedly had an impact on the channel stability in the critical area between Hamilton and Stevensville. Figure 9 also shows how mean flows for each month in 1948 differed from average mean monthly flows for the period of record. Another 35-year flood occurred in 1974 at Darby. Hydrographs of an average year (1975) and a flood year (1974) at the USGS gaging station near Darby are presented in Figures 14 and 15, respectively.

The Bitterroot River at its confluence with the Clark Fork in Missoula has a maximum mean monthly flow of about 8,500 cfs (Figure 16). Peak flows were highest in 1947, 1948, 1956, 1972 and 1974 (Figure 17). The 1947 and 1948 floods as well as the 1972 and 1974 floods represent excessively high peak flows occurring within consecutive or nearly consecutive years. Such short intervals between two high-flood years aggravates channel stability by preventing the river from establishing a consistent course. Peak flows and low flows were computed based on flows in the Clark Fork above and below Missoula (Figures 17 and 18). Both Rattlesnake Creek and the Bitterroot River enter between these two gaging sites. Corrections were not made for the flow entering from Rattlesnake Creek. Therefore, these values represent relative changes in peak flows over the years, rather than absolute flows of the Bitterroot River at Missoula. Peak flows at this site have also increased since 1947. The mean peak flow for 1930 to 1946 is only 11,200 cfs, while the mean peak flow for 1947 to 1978 is 16,700 cfs. Average low flows

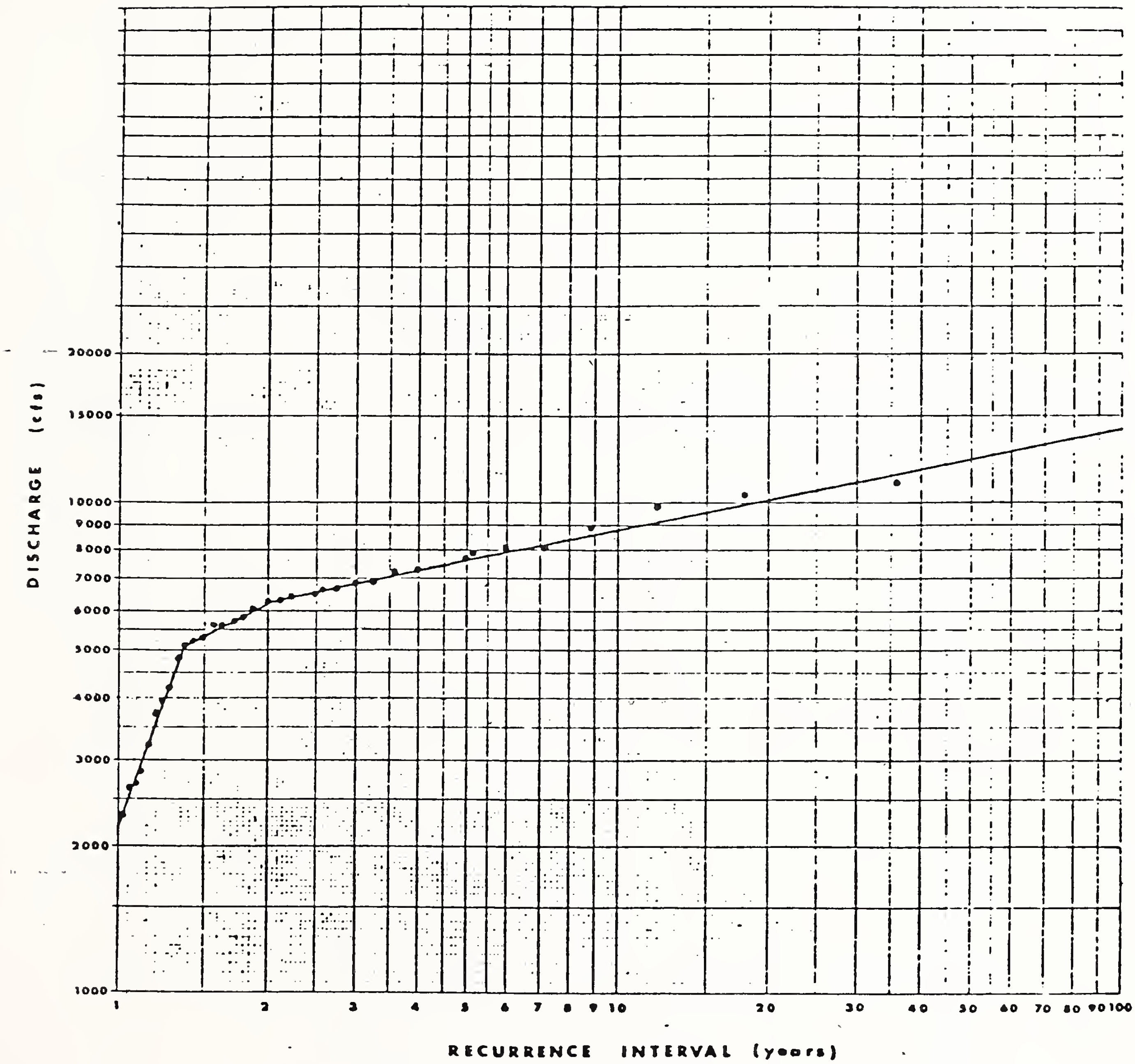


Figure 13. Flood Frequency Graph for Bitterroot River Near Darby Gaging Station.
(Reproduced from Nolan, 1973)

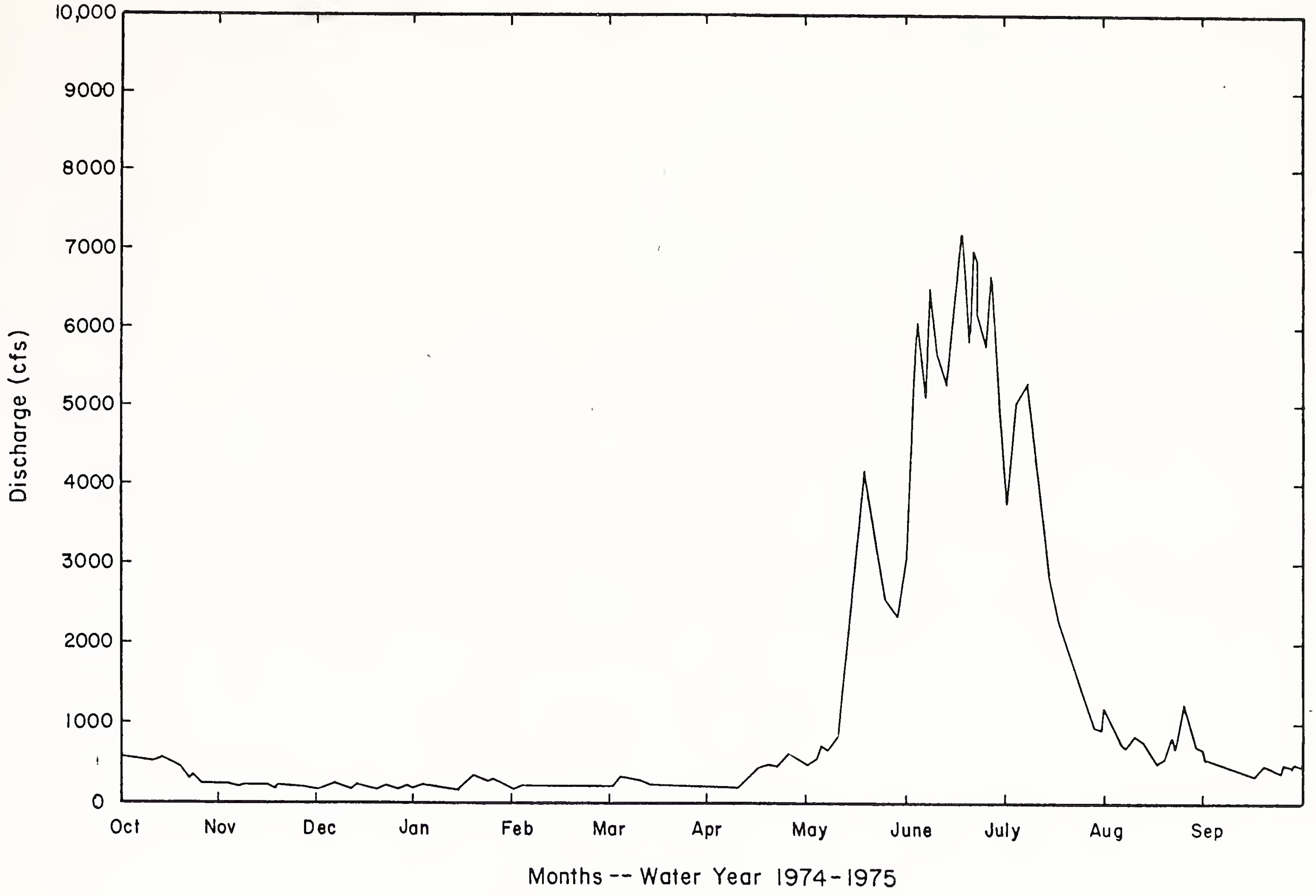


Figure 14. Bitterroot River Near Darby: 1975 (Average Year)

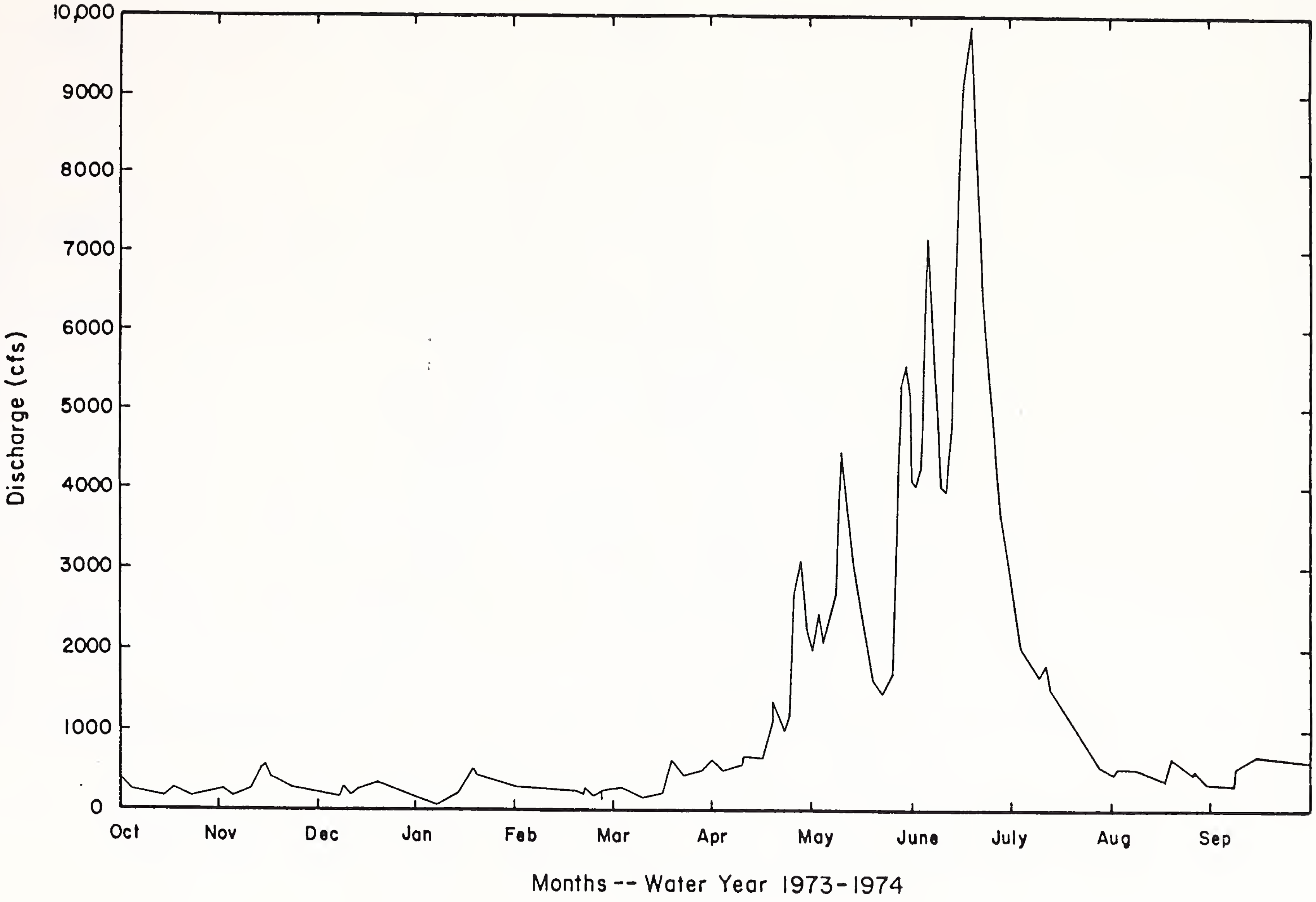


Figure 15. Bitterroot River Near Darby: 1974 (Flood Year)

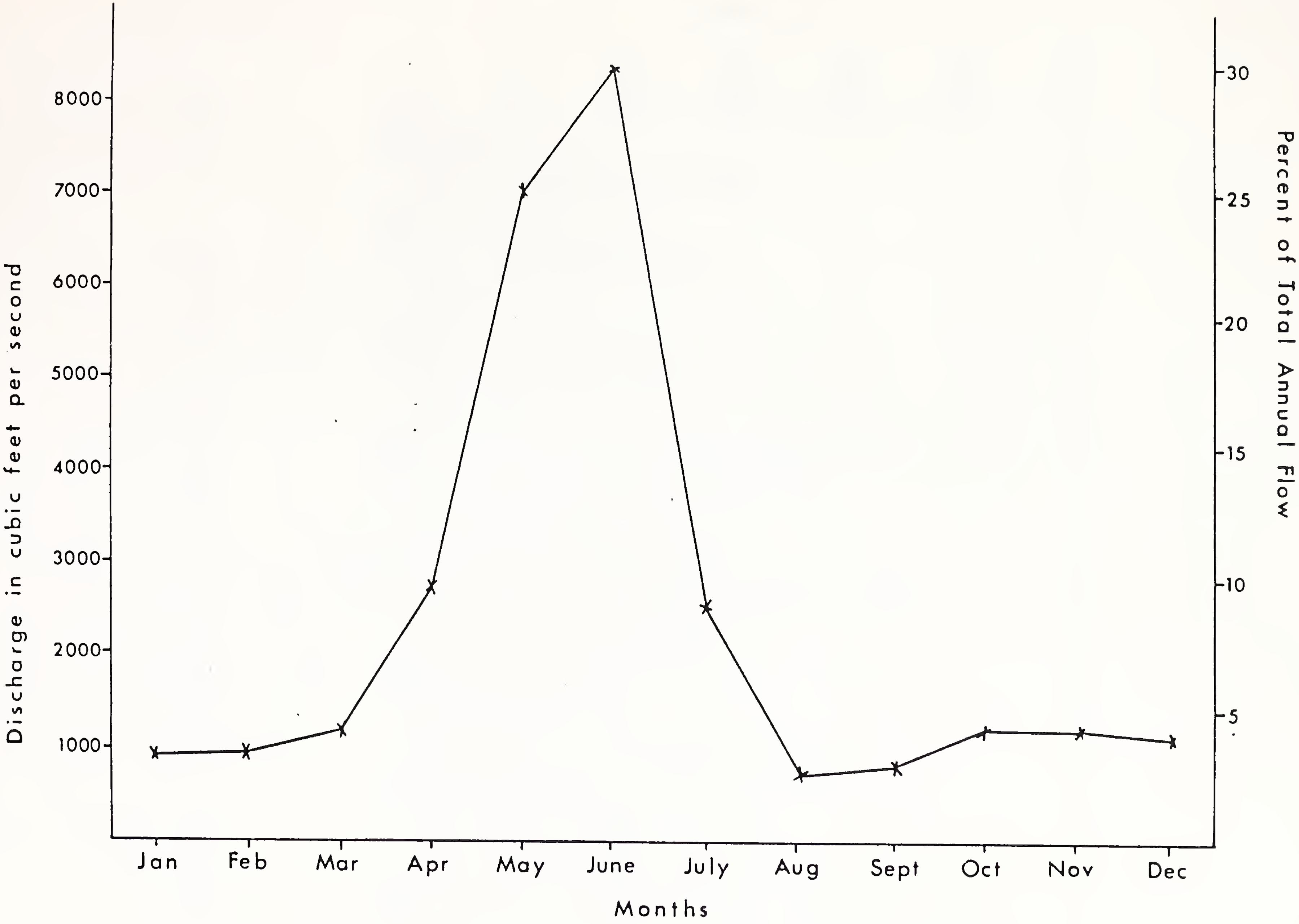


Figure 16. Mean Monthly Flows for the Bitterroot River at Mouth
From: Senger, 1975

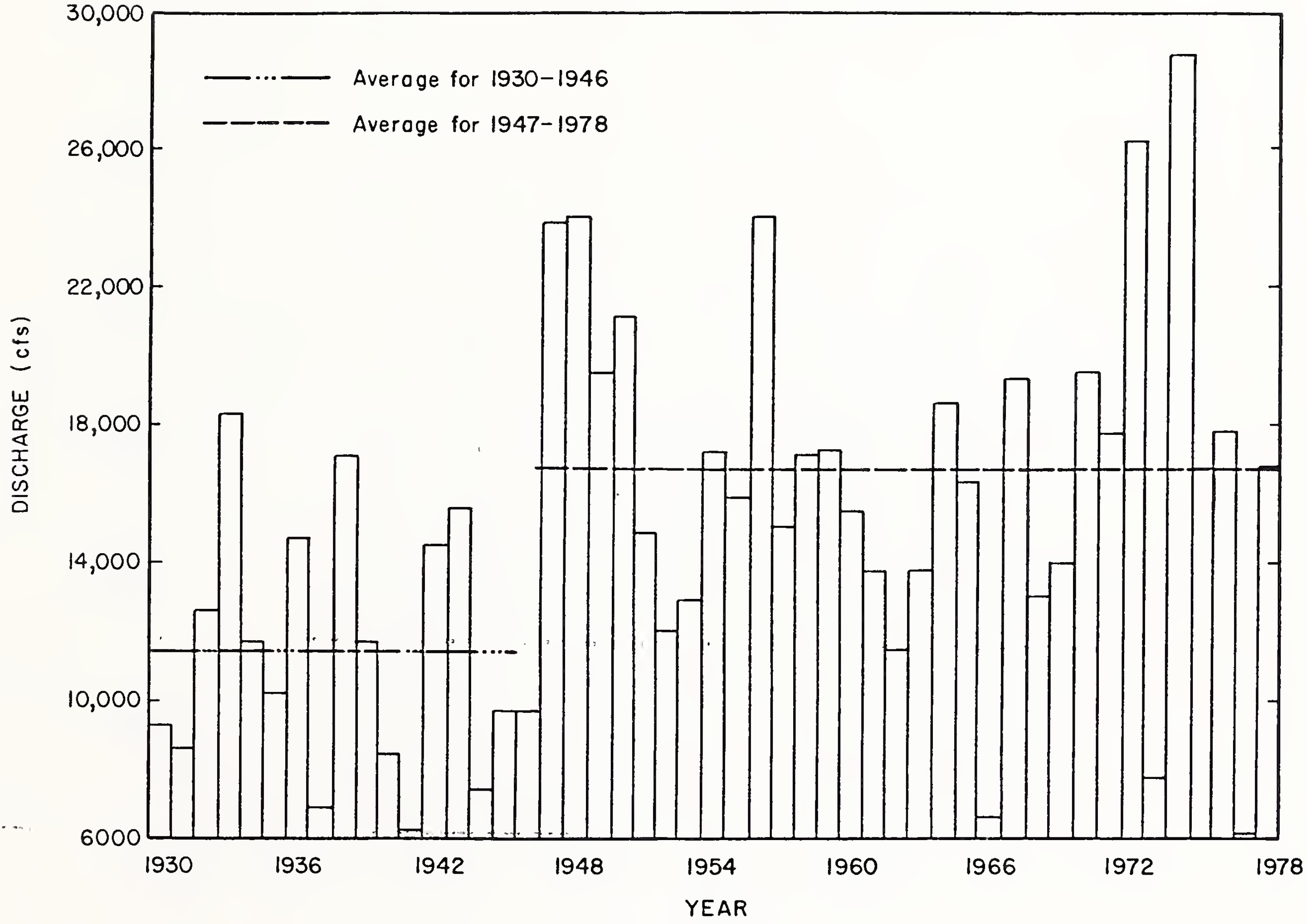


Figure 17. Peak Flows: Bitterroot River at Missoula: 1930-1978

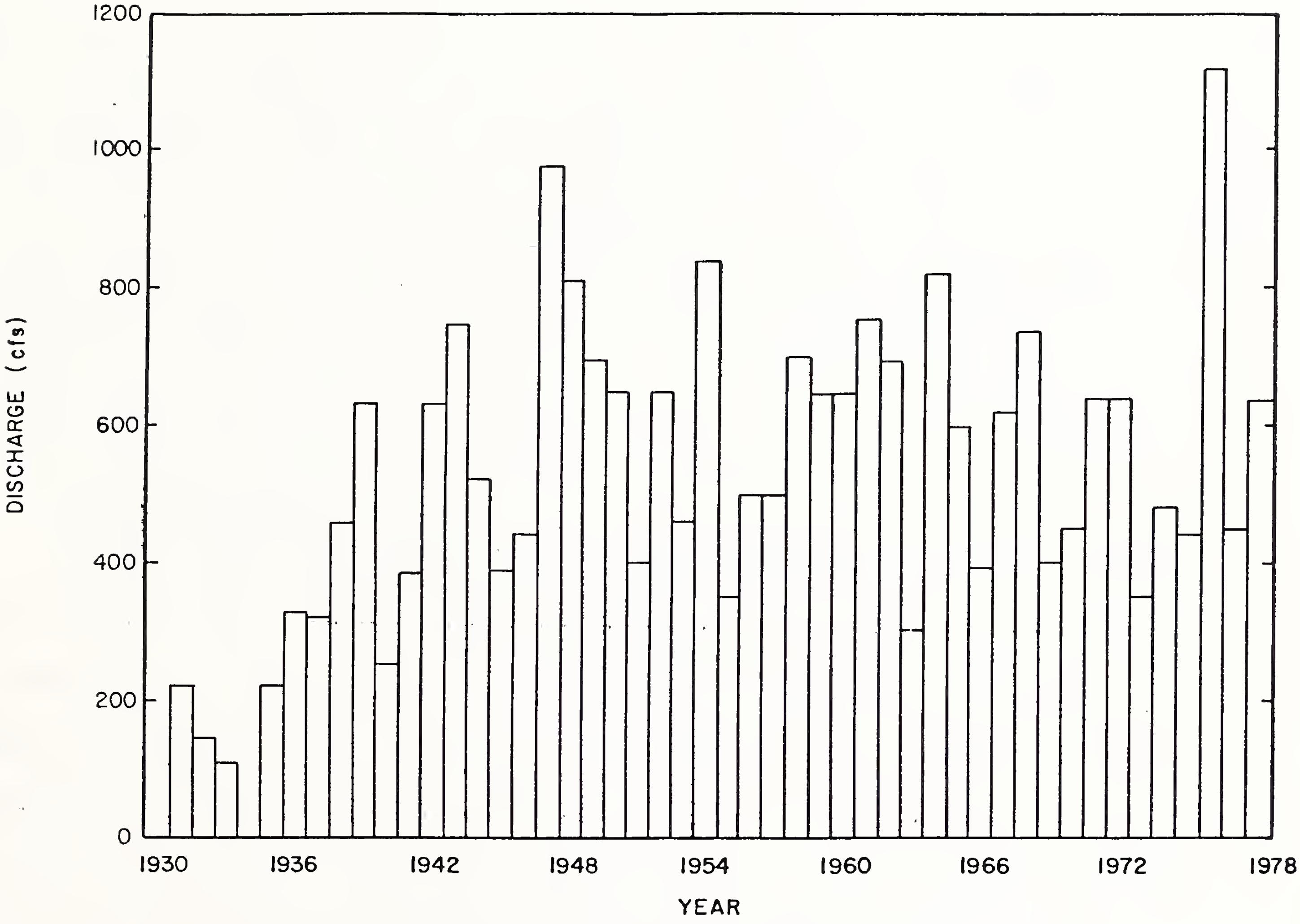


Figure 18. Lowest Flows: Bitterroot River at Missoula: 1930-1978

have also increased since 1947 (Figure 17). The largest known flows of the Bitterroot River at its mouth occurred in 1899 and amounted to about 38,000 cfs. This flow was greater than the 100-year flood (Figure 19). Although the 1948 Bitterroot River flood represented a 35-year flood in Darby, the flow of about 23,000 cfs at Missoula was only a 22-year flood (Figure 19). The 1972 was only an 18-year flood at Darby, but represented a 55-year flood at Hamilton and a 45-year event at Missoula. Another major flood event occurred again only two years later in 1974. This flow represented a 35-year flood at Darby, a 50-year flood at Hamilton and approximately a 65-year flood at Missoula. These rare flood events, occurring only one year apart as in 1947 and 1948 and only two years apart as in 1972 and 1974, are largely responsible for sudden shifts in the channel's location.

TRIBUTARY STREAM FLOW

The west-side tributaries exhibit greater seasonal fluctuations than do east-side streams. Shallow soils and glacier-scoured rocks are largely responsible for the flashy streamflow characteristics of the Bitterroot Mountain streams. Up to 75 percent of the average annual streamflow occurs during May, June and early July, while as little as 3 percent occurs during August and September. Peak flows generally occur in late May and early June. The runoff pattern from these drainages is typical of mountainous areas where snowmelt provides the bulk of the flow. Hydrographs are shown for Bear Creek (west-side tributary) and Burnt Fork and Willow Creeks (east-side tributaries) (Figure 20). Bear Creek, draining 26.8 mi^2 at the gaging site, experienced a high of 600 cfs in late May and a low of 3 cfs in September. Even though Burnt Fork Creek drains 74 mi^2, nearly three times as much area, its peak flow is half that of Bear Creek.

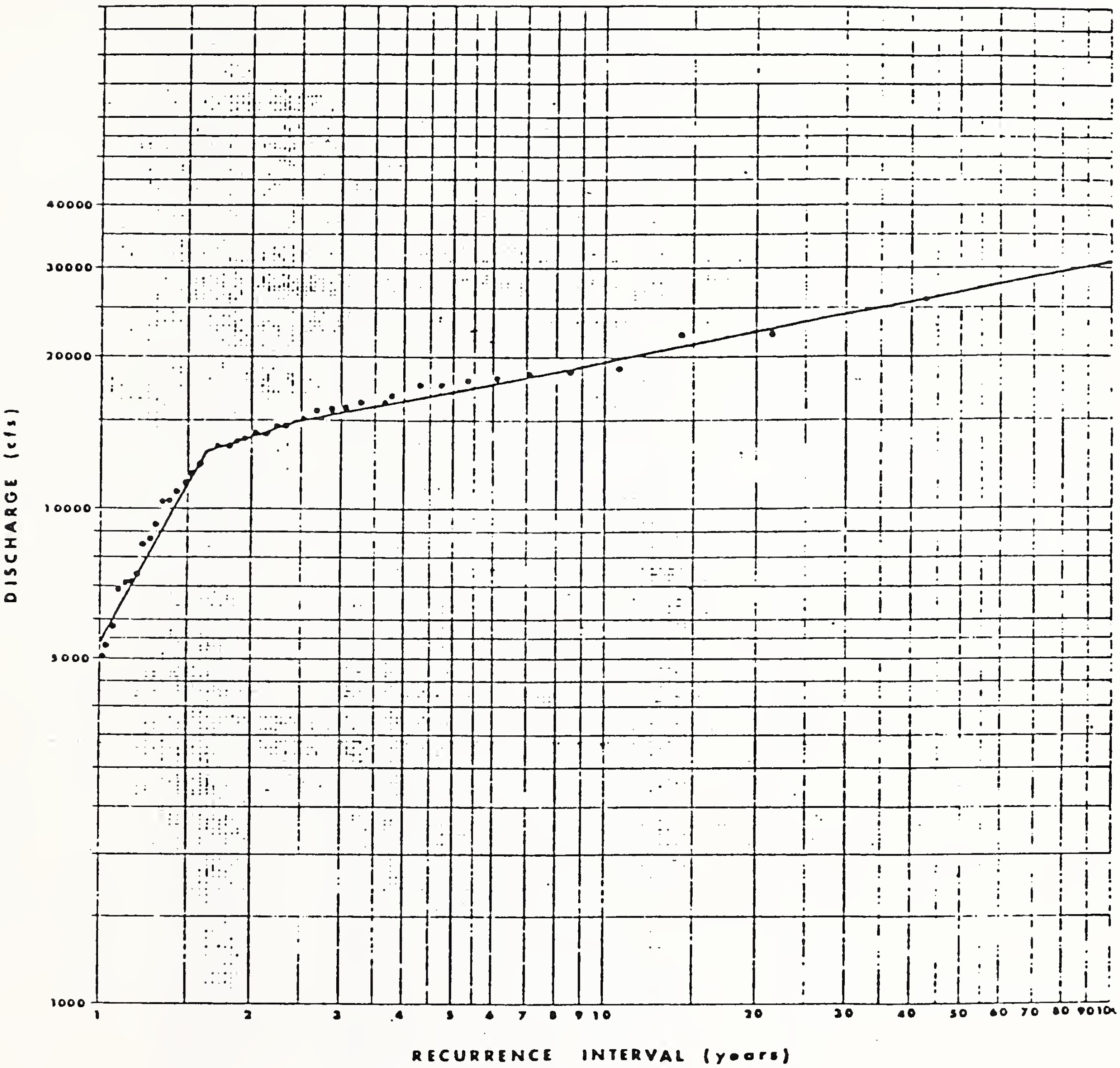


Figure 19. Flood Frequency Graph for the Bitterroot River at Mouth
(Reproduced from Nolan, 1973)

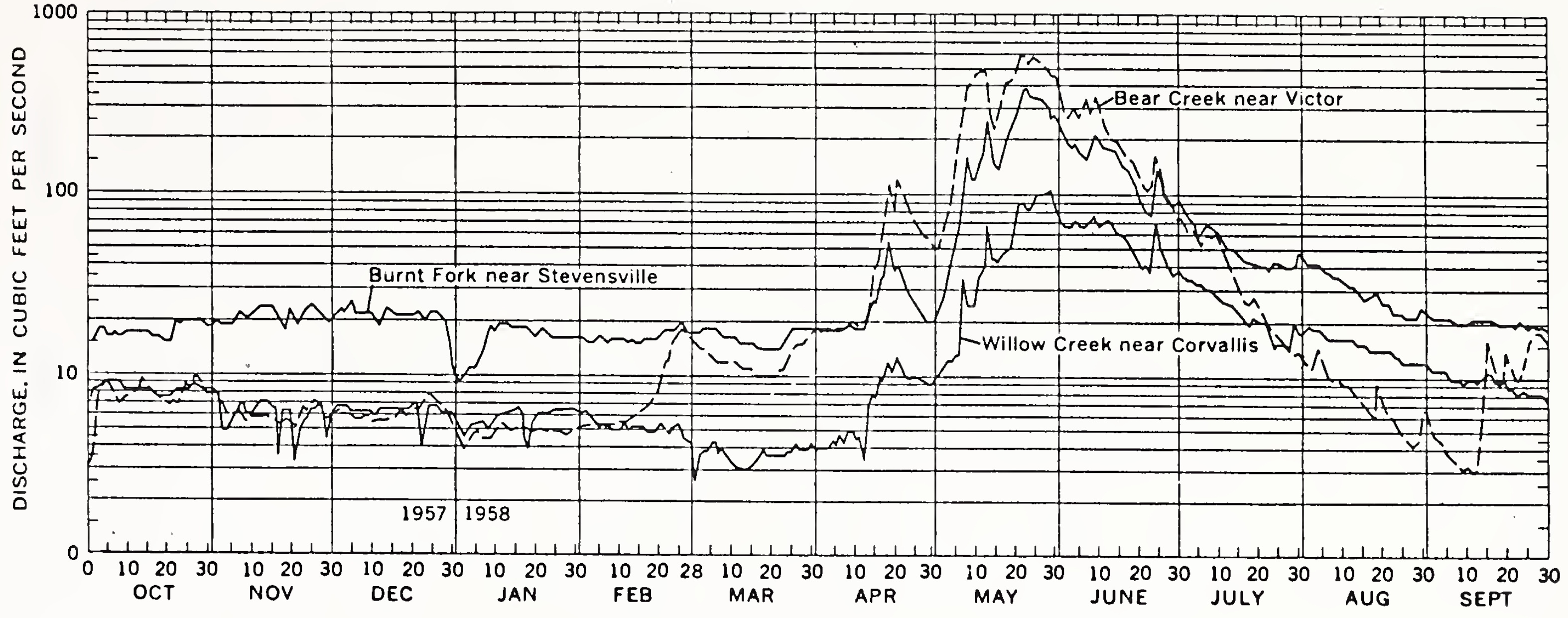


Figure 20. Hydrographs of Typical Bitterroot River Tributaries, 1958 Water Year
From: McMurtrey et al, 1972

Figure 21 illustrates the differences in response of west-side and east-side tributaries. An average of 40 percent of the annual precipitation becomes streamflow in the west-side tributaries, while an average of 24.5 percent becomes streamflow in the east-side tributaries. This difference is partly due to the shallower, more rocky soils with less vegetative cover on the west side.

Flood frequency graphs also illustrate the differences in flow characteristics between east and west-side streams. Recurrence intervals for flows of a specific magnitude are longer for east-side than for west-side tributaries. For example, a flow of 800 cfs is expected to occur once every [illegible] years in Bear Creek, while this same flow is expected to occur only once [illegible] 45 years in Burnt Fork Creek (Figure 22). The flow duration curve for Bear Creek indicates that 10 percent of the time the flow is greater than 200 cfs and that 10 percent of the time it is less than 5 cfs (Figure 23). Fifty percent of the time the flow is less than 20 cfs. The curve indicates that flows above 500 cfs only occur about 1 percent of the time. This graph illustrates the flashy characteristics of streamflows regulated by snowmelt runoff. Hydrographs of mean monthly flows for a few of the major tributaries are presented in Figures 24 through 27. Again, these graphs indicate a tremendous increase in flow during the snowmelt season in May and June.

3.4.4 Irrigation and Reservoirs

Approximately 111,000 acres in the Bitterroot Valley are irrigated (Senger, 1975). Surface water provides nearly all of the irrigation water, with groundwater supplying only about 3,000 acres. About one third of the irrigated land in the valley is supplied by the Bitterroot River, while the remainder is supplied by tributary flow. Appropriations exceed stream flow

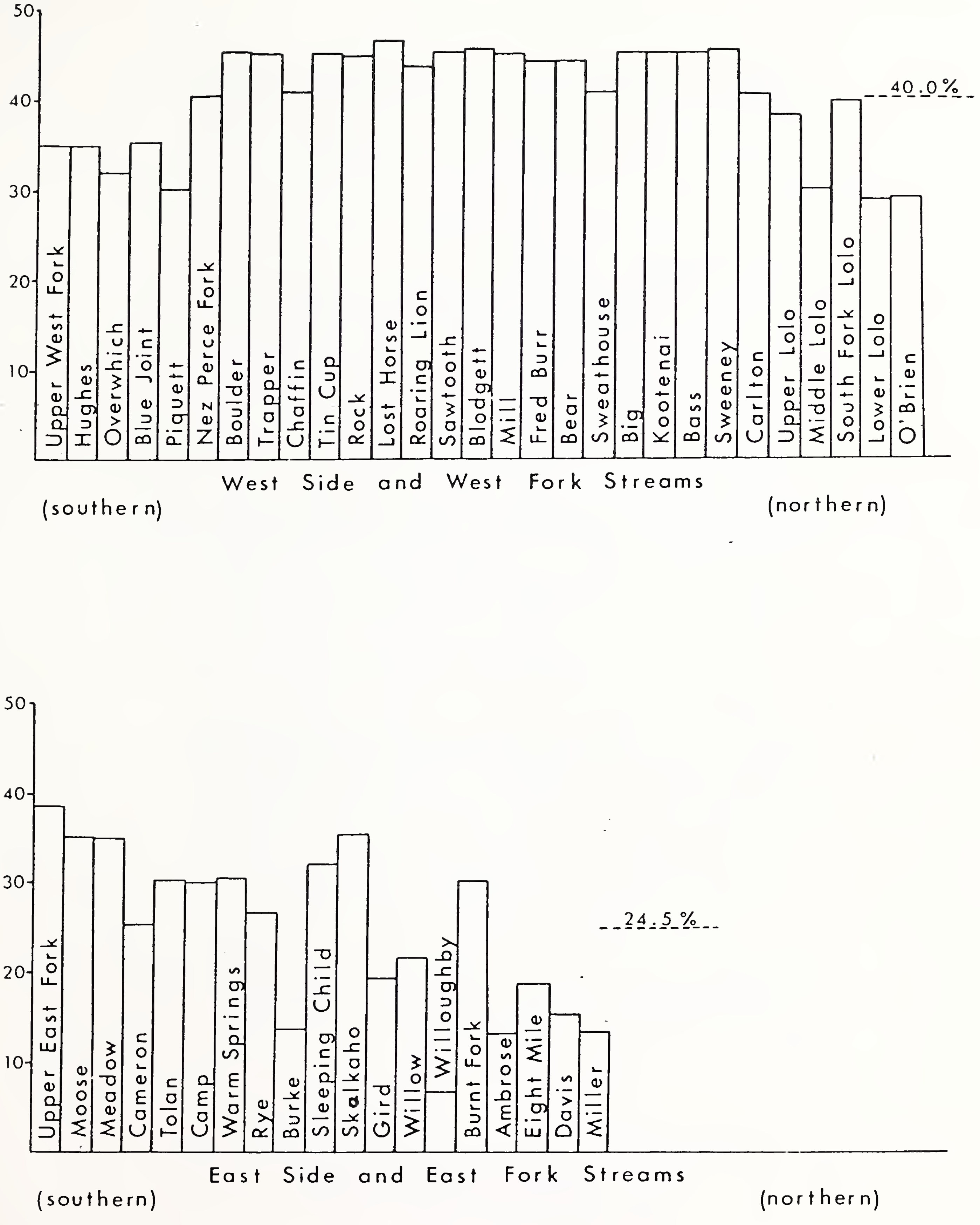
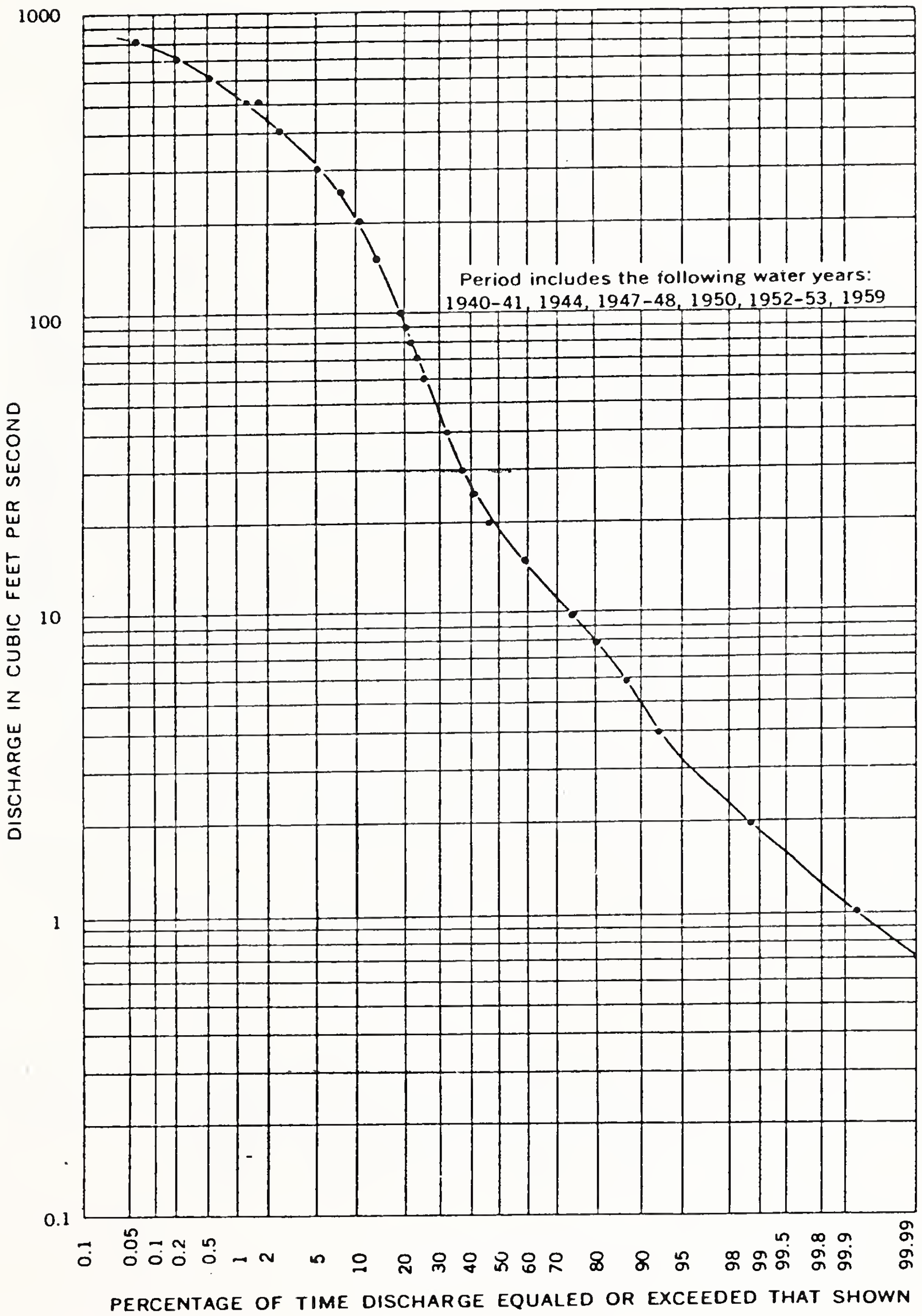


Figure 21. Percent of Average Annual Precipitation that Becomes Stream Discharge in All Subwatersheds in the Bitterroot Drainage
From: Senger, 1975



Period includes the following water years: 1940-41, 1944, 1947-48, 1950, 1952-53, 1959

Figure 23. Flow Duration Curve of Daily Flows of Bear Creek Near Victor.
From: McMurtrey et al, 1972

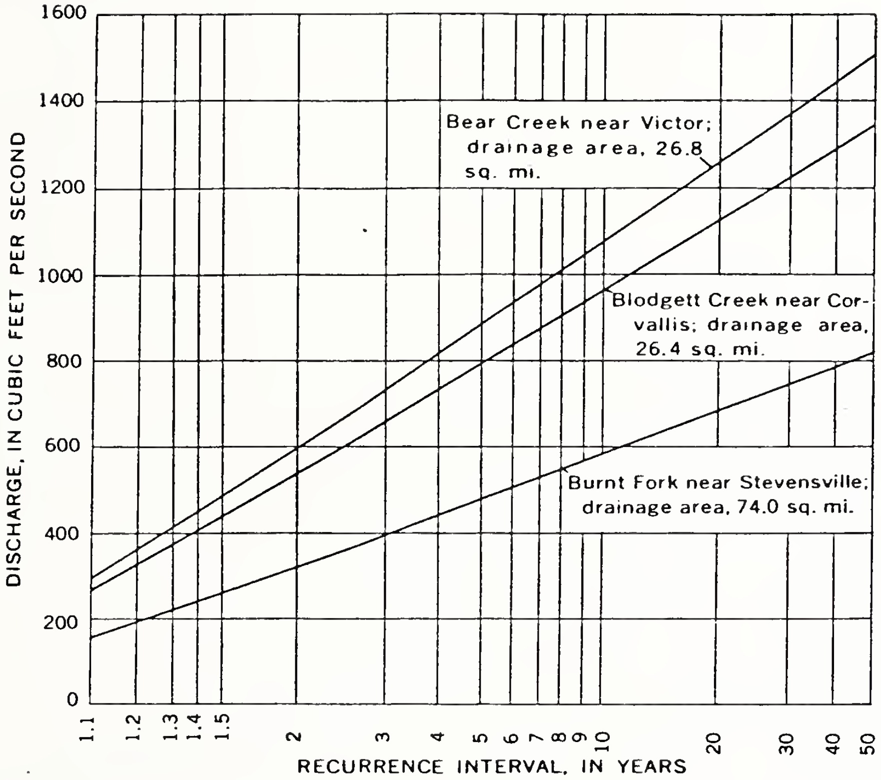


Figure 22. Frequency of Annual Floods for Some Typical Bitterroot River Tributaries.
From: McMurtrey et al, 1972

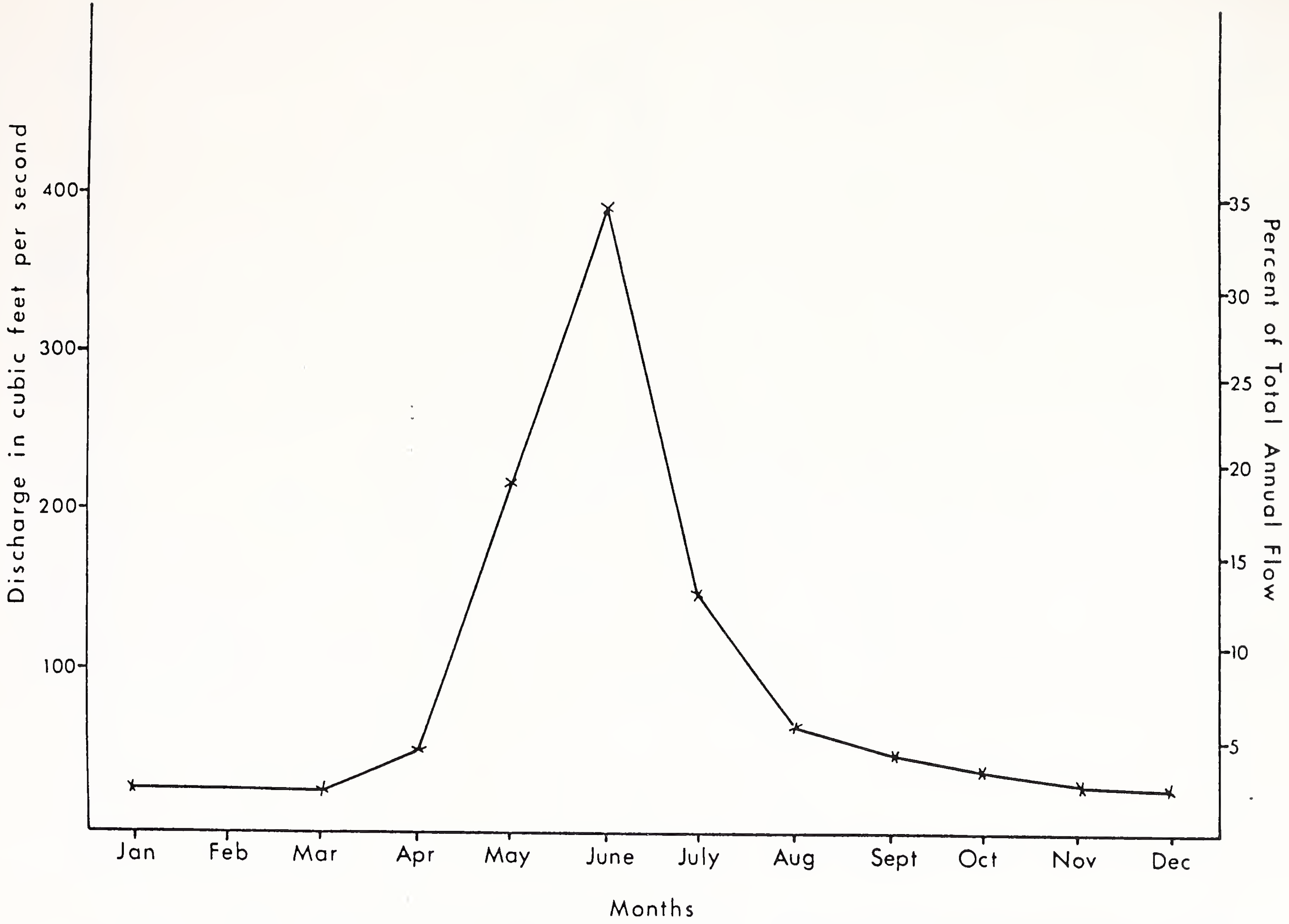


Figure 24. Mean Monthly Flows for Skalkaho Creek
From: Senger, 1975

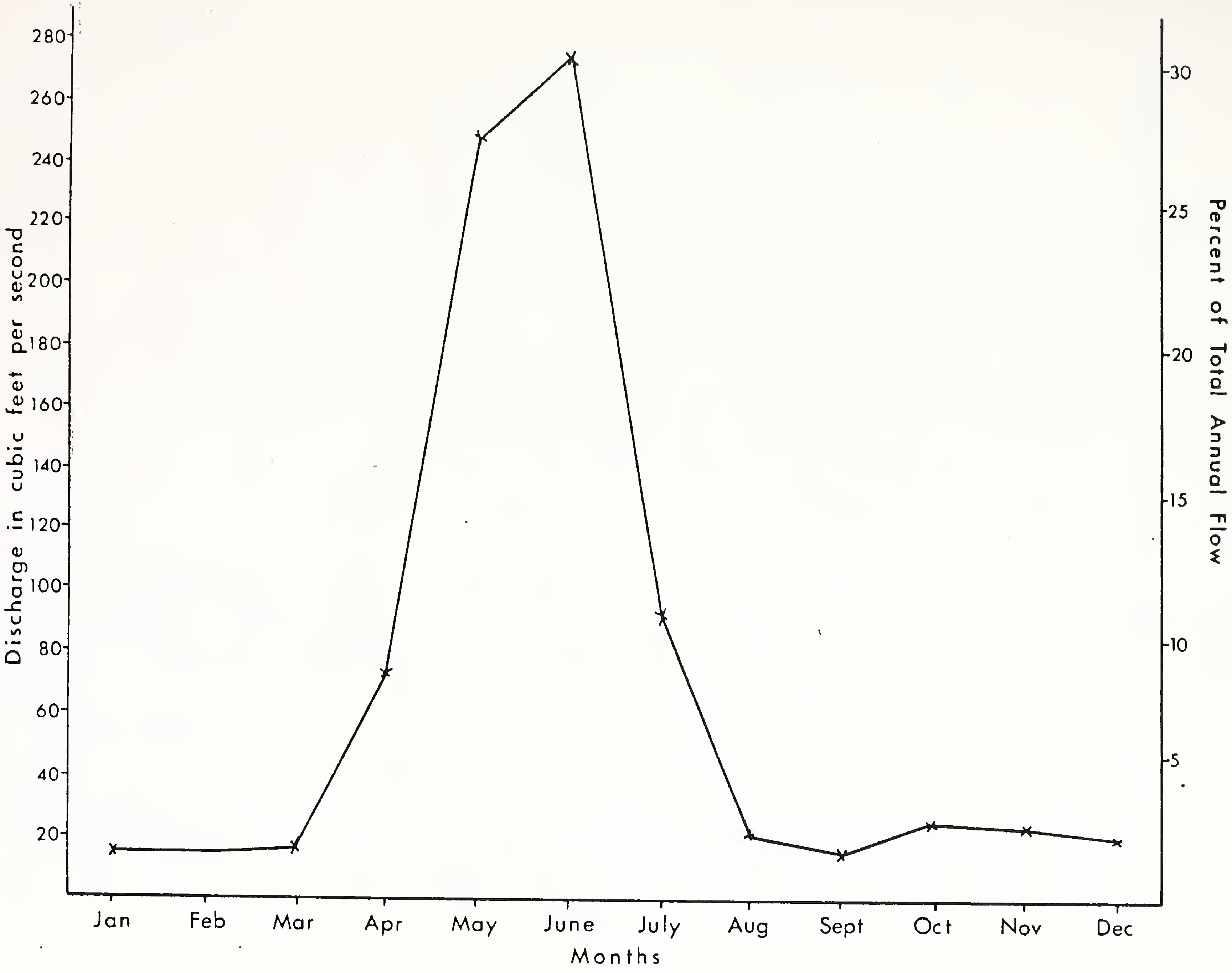


Figure 25. Mean Monthly Flows for Blodgett Creek
From: Senger, 1975

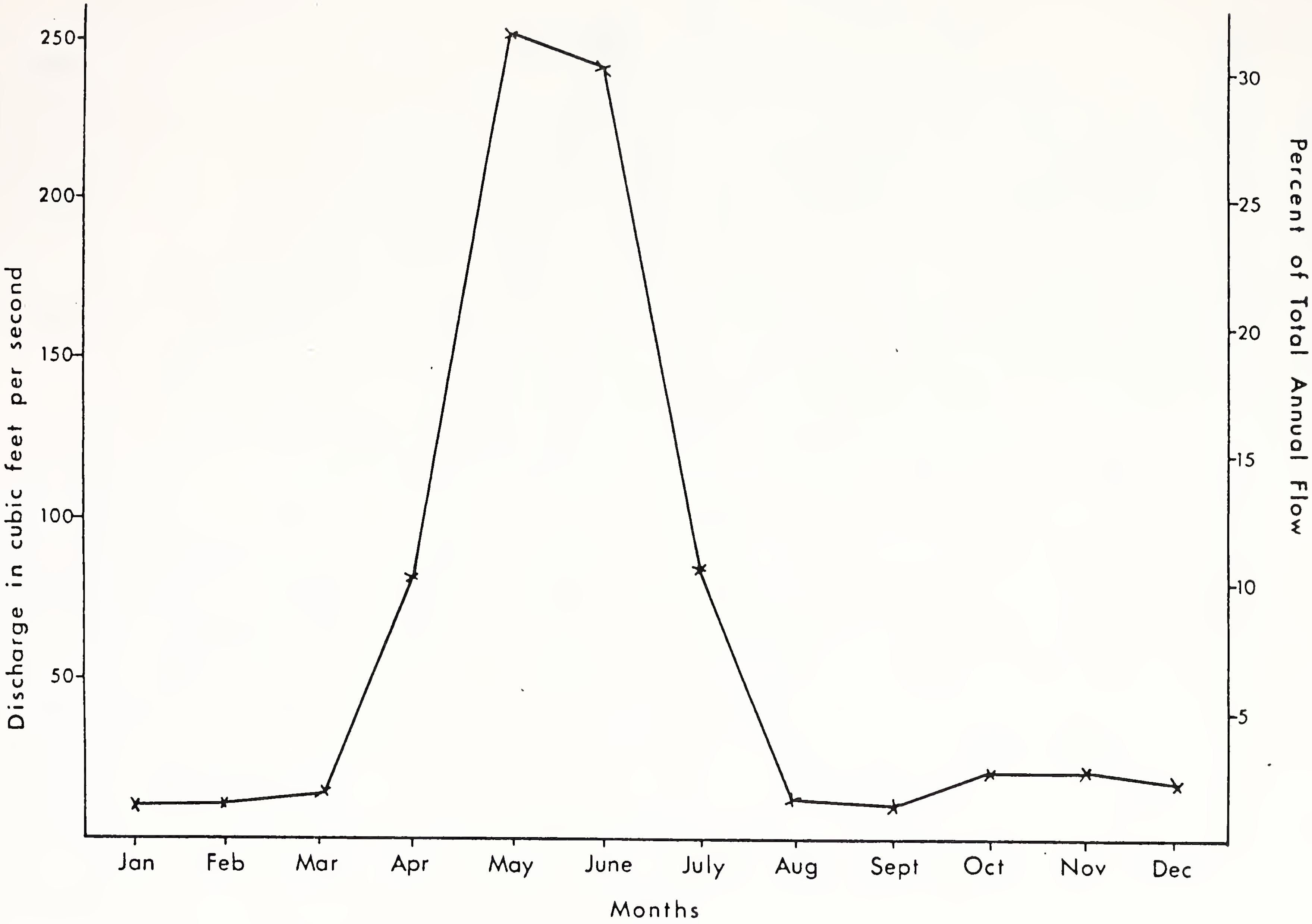


Figure 26. Mean Monthly Flows on Bear Creek
From: Senger, 1975

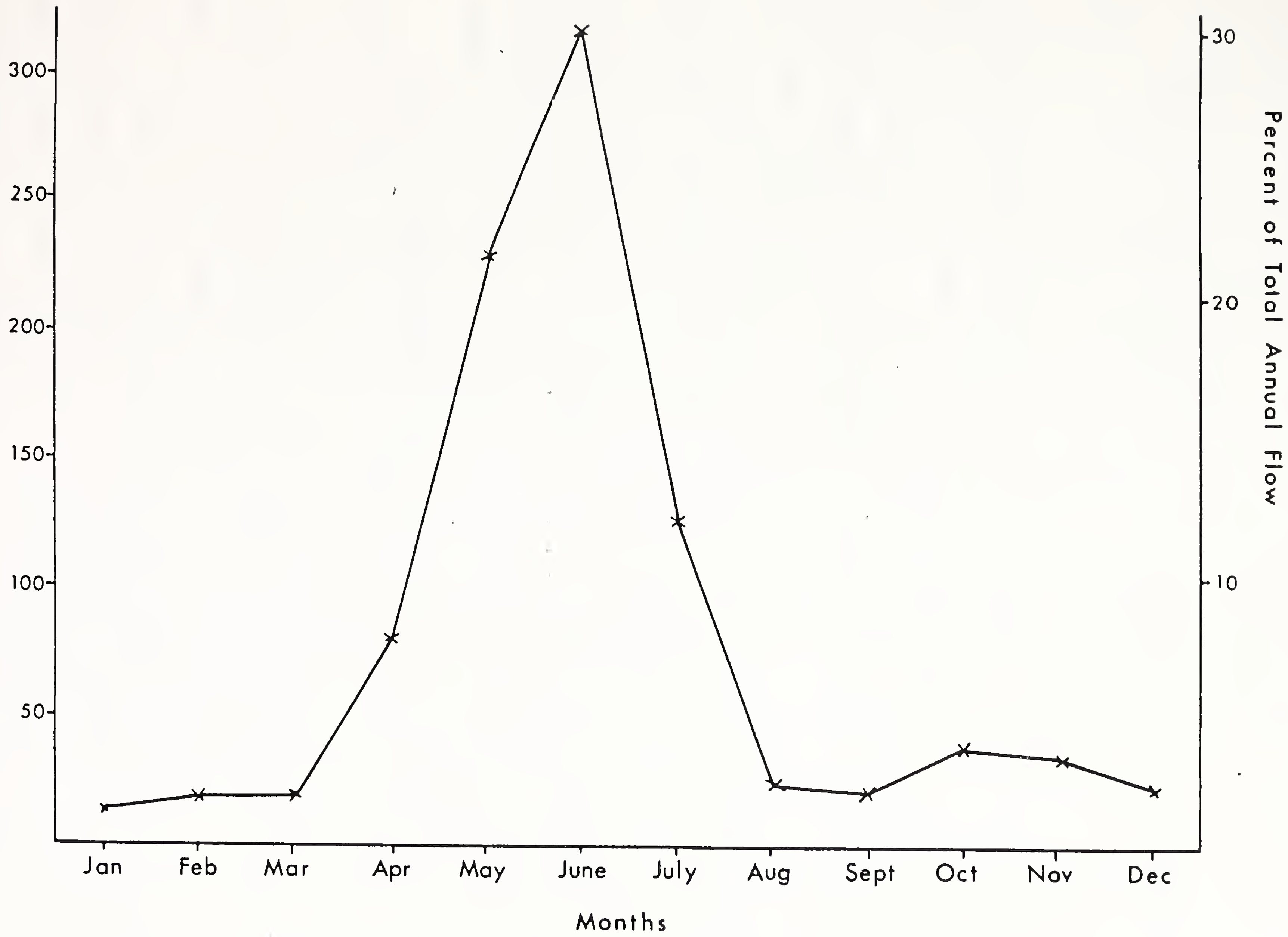


Figure 27. Mean Monthly Flows on Kootenai Creek
From: Senter, 1975

and all rights can be filled only during peak flows. Figure 28 shows the approximate amount of water diverted throughout the year. Peak consumptive use occurs in late July and early August.

Two major reservoirs have been constructed for storage of irrigation water. Painted Rocks Lake on the West Fork of the Bitterroot River was completed in 1940 and has a storage capacity of 31,700 acre-feet. However, it remains essentially unused for irrigation purposes. Some of the water has been purchased to augment low flows and consequently improve trout habitat in the Bitterroot River. Lake Como on Rock Creek was created in 1909 and has a storage capacity of 34,800 acre-feet. About 19,000 acres are irrigated from Rock Creek, mainly on the east side of the valley.

A total of 26 small dams are currently operated on high lakes in the Bitterroot and Sapphire Mountains (Table 4). These dams store a total of 14,500 acre-feet. Twenty-seven other small dams which were previously maintained for irrigation have since reverted to Forest Service ownership and are no longer maintained. Several potential dam sites have been proposed by various agencies and are presented in Table 5 (Garn and Malmgren, 1973).

The total storage capacity of all the reservoirs currently in use is 81,000 acre-feet. This value represents only 5 percent of the total volume of water annually discharged at the mouth of the Bitterroot River. Unless an excess of at least 20 percent of the annual runoff is stored in reservoirs, the impoundments have virtually no effect in reducing peak flows.

A complex network of ditches extends throughout the valley. Late season water shortages are a result of inefficient water distribution. People in bottom lands that are underlain by good aquifers have senior water rights. Ideally, these people could pump groundwater and leave stream flow to be used by owners of high lands where adequate groundwater yields cannot be acquired.

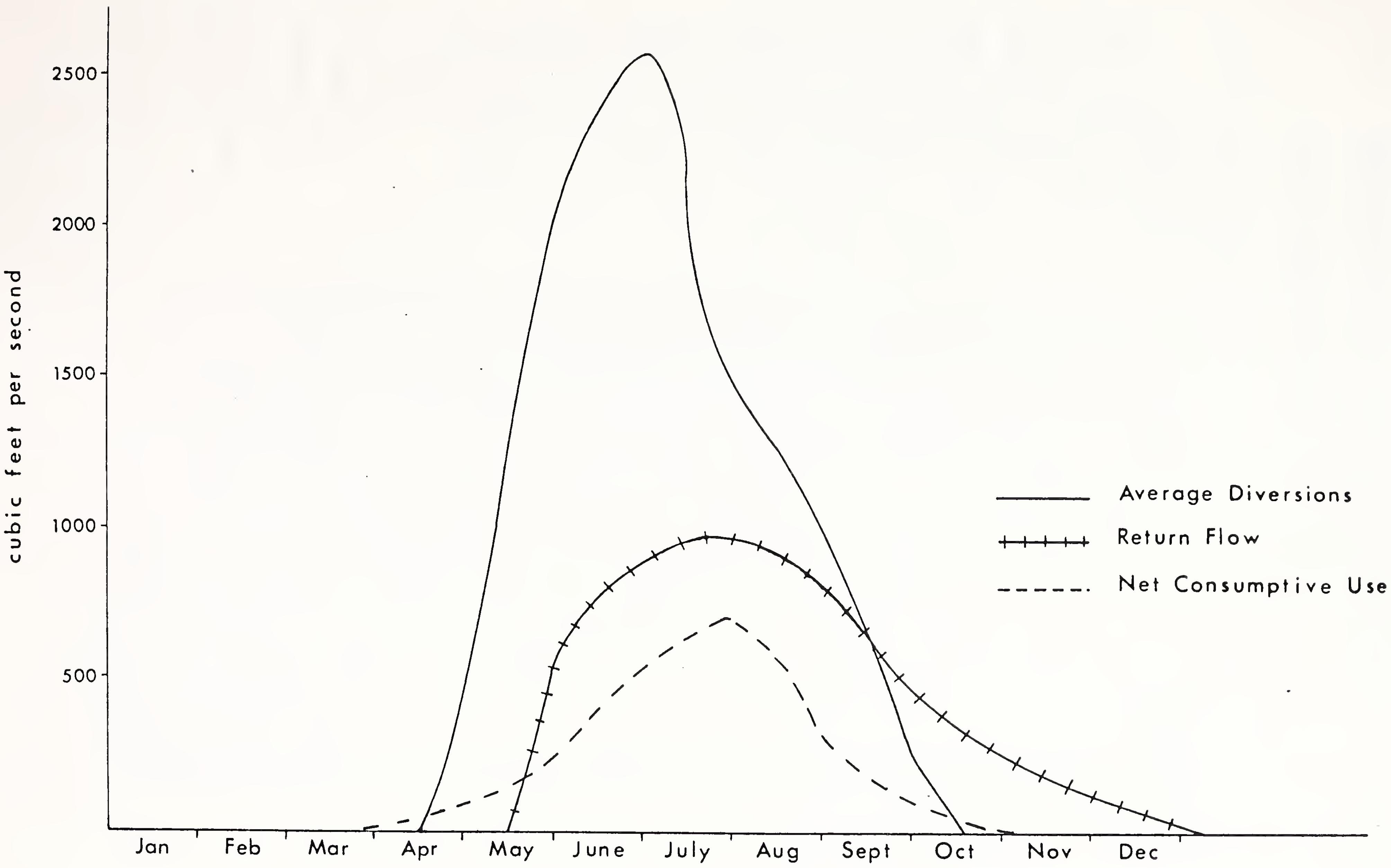


Figure 28. Pattern of Diversions, Return Flow, Consumptive Use (from Senger, 1975).

Table 4. Small Dams Currently Operated in the Bitterroot and Sapphire Mountain, Bitterroot Drainage.

From: Garn and Malmgren, 1973.

Name	Drainage	Storage Capacity (acre-feet)
Bass Lake	Bass Creek	3,600
Big Creek Lake	Big Creek	2,781
Blodgett Lake	Blodgett Creek	336
Boulder Lake	Boulder Creek	140
Burnt Fork Lake	Burnt Fork	510
Canyon Lake	Canyon Creek	475
Carlton Lake	Carlton Creek	450
Dam Creek Lake	Dam Creek	120
Fred Burr Reservoir	Fred Burr Creek	515
Fred Burr Lake	Fred Burr Creek	200
Gleason Lake	Willow Creek	180
Hauf Lake	Mill Creek	130
High Lake	Blodgett Creek	743
Holloway Lake	Sweeney Creek	280
Knaack Lake	Sheafman Creek	25
Kent Lake	Skalkaho Creek	48
Lappi Lake	Bass Creek	35
Lower Twin Lake	Lost Horse Creek	400
Mill Lake	Mill Creek	670
Reed Lake	One Horse Creek	37
Sears Lake	Mill Creek	75
Sheafman Lake	Sheafman Creek	20
Tamarack Lake	Chaffin Creek	114
Tin Cup Lake	Tin Cup Creek	2,200
Upper Twin Lake	Lost Horse Creek	220
Wyant Lake	Canyon Creek	200
	Total	14,504

Table 5. Potential Dam Sites in the Bitterroot River Valley

Name	Stream	Location T. R. Sec.	Storage (Acre-ft.)	Proposing Agency
Bear Cr.*	Bear Cr.	7N 21W 8	2,155	MWRB
Lake Como Res.*	Rock Cr.	4N 21W 32	53,600	Bur. of Rec.
Lomo Irrig. Dist.*	Blodgett Cr.	6N 22W 17	10,500	MWRB
South Lake*	Kootenai Cr.	9N 22W 14	2,614	MWRB
Upper Sula*	East Fork	1N 19W 17	60,000	Bur. of Rec.
Blodgett No. 1	Blodgett Cr.	6N 22W 15	67,500	Bur. of Rec.
Blodgett No. 2	Blodgett Cr.	6N 22W 15-16	60,500	Bur. of Rec.
Coyote Meadows	Sleeping Child Cr.	4N 18W 20	1,100	SCS

* Source: Montana Water Resources Board, 1969.

From: Garn and Malmgren, 1973.

However, senior water rights are exercised, and water users on the benches and terraces are left with inadequate water supplies during late summer.

3.5 Land Use Practices

Ravalli County was first settled because of its rich farming lands; agriculture is still important in the area. Irrigation farming produces forage crops, grains, potatoes, and fruit. Beef and dairy cattle are also important. Lumber is presently the chief industry in the valley. Lodgepole pine, Douglas fir and ponderosa pine are logged for house logs, pulp wood, and lumber. Tourism and recreation are important additions to the economy of the area. The Selway-Bitterroot wilderness in the western part of the watershed offers outstanding recreational opportunities. The Bitterroot Valley has recently experienced an influx of retired and semi-retired persons. Much of the valley has been subdivided into small acreages, providing "ranchettes" for people desiring retirement in a rural setting. Such ranchettes also appeal to commuters working in Missoula.

Sediment yield from a watershed is a function of land use practices. Large-scale changes in vegetation resulting from fire, logging practices, land conversion and urbanization can increase total sediment yield from a watershed. Small-scale changes made at the local level can also increase sediment yield. Bank protection techniques utilized by one landowner can result in increased bank erosion on neighboring land. Knowledge of the changes in land use over a long period of time is essential to understanding present conditions in the Bitterroot watershed.

Increases in the flow and sediment supply to a river can accelerate channel instability. The effects of several different activities can accumulate and contribute to channel braiding. Since man's activities in the area have intensified during the past century, the river system may have

been impacted to some extent. Disturbances to the land surface and stream channels can accelerate erosion and increase sediment loads into the Bitterroot River. Early in the 1900's the east-side slopes were heavily grazed by sheep. Overgrazing can increase erosion rates from the slopes, as well as from creek banks. Animals tend to trample creekside areas, dislodging sediment and altering natural bank slopes and channel shapes.

Poor logging practices can also adversely impact a river system. In the past, horse logging methods involved hauling logs down the center of the stream channels. This practice gouged out sediments and destroyed the natural channel configuration. Even today, some of these channels have not yet recovered (Hammer, 1980). Later, tractor logging was introduced and steep slopes were indiscriminately logged with heavy machines that tore up the ground. Poor quality roads were constructed with no consideration of disturbances to the watershed. Poorly designed dirt roads can be a significant source of sediment during heavy rains. Very often, no culverts were installed when roads crossed creeks. Present logging practices are carefully planned to minimize erosion, yet it is conceivable that the sediment produced during the past could still be moving through the system, affecting channel morphology. Huge clearcuts have been made in the past. Clearcutting can affect snowmelt timing, water yield, and sediment yield from an area. In the past, clearcutting and terracing the area for planting purposes "undoubtedly increased peak flows generated from cut-over areas" (U.S. EPA, 1975).

Poor forest management on private lands produces large amounts of sediment. The EPA (1975) reported that some stream channels were filled with debris and soil and that heavy equipment had been operating within the stream channel. This particular area was on private ground adjacent to Forest Service Land. Such abuse degrades water quality and contributes sediment to the Bitterroot River.

The EPA also identified a significant source of sediment loading to Sleeping Child Creek. Resort construction at Sleeping Child Hot Springs produced about half of the sediment load carried by the stream (EPA, 1975).

The Sleeping Child Burn in 1961 accelerated erosion and channel degradation. This fire burned a total of 28,000 acres of land, leaving the soil in a hydrophobic state which consequently amplified runoff and sediment yield. The fire burned an estimated 7,526 acres at the head of the Sleeping Child drainage. A substantial area of bare ground existed as much as 12 years after the fire and sheet erosion carried off much of the thin topsoil (Garn and Malmgren, 1973). After the fire, salvage operations attempted to harvest the logs as quickly as possible. Substandard roads were constructed too close to stream channels. Additionally, materials were apparently cast down into the channels during road maintenance.

Various types of timber harvesting may also have augmented stream flow in this drainage. Most of this logging occurred after 1965 in the form of clearcutting, overwood removal and shelterwood cutting. Vegetative removal in the Sleeping Child drainage is summarized in Table 6. Total disturbance, including the fire, amounted to 23 percent of the total drainage area. The burned area represented only a small portion of the entire drainage, yet it amounted to 55 percent of the upper drainage area, above the confluence with Divide Creek. The fire resulted in extensive damage to the stream channel in the upper Sleeping Child drainage. The magnitude of the peak flows increased, creating severe erosion and channel deterioration. Sand and gravel sized sediments were flushed downstream, scouring some reaches and later settling out and burying aquatic vegetation (Garn and Malmgren, 1973).

Table 6. Vegetative Removal by Subdrainages of the Sleeping Child Drainage.

From: Garn and Malmgren, 1973

Subdrainage	Drainage Area (Acres)	Clearcut (Acres)	Overwood Removal (Acres)	Shelterwood & Selection (Acres)	Sleeping Chile Fire (Acres)
1. Upper Sleeping Child	10,000	0	0	0	5,542
2. Divide Creek	11,370	600	0	0	1,984
3. Middle Sleeping Child	5,370	111	0	0	--
4. Two Bear Creek	6,510	417*	0	373	--
5. Lower Sleeping Child	9,710	1,112	587	556**	--
Entire Drainage	42,960	2,240	587	929	7,526

* Includes 250 acres of hazard reduction.

** Includes 214 acres of selection logging.

Below Divide Creek the channel flows through stable rock for some distance. However, in the lower Sleeping Child drainage, the stream flows through unstable alluvium from the National Forest boundary to its confluence with the Bitterroot River. Since much of the protective streamside vegetation has been removed by overgrazing or clearing, high flows in Sleeping Child Creek have degraded the channel in this lower reach. Tree growth in the Sleeping Child Burn is limited because of shallow soils and high elevations (short growing season). Eleven years after the fire, regenerated timber averaged less than three feet tall. Thus, hydrologic recovery of the burned area to preburn conditions may take as long as 50 years. Since 1973, timber harvesting has been deferred in the upper drainage, and in the lower drainage cutting has been "hydrologically designed to avoid synchronization of stream flows and cumulative effects of increased runoff" (Garn and Malmgren, 1973).

Irrigation practices have also altered flow and sediment loads. Dam construction and maintenance has very likely affected sediment production. Reservoirs serve as sediment traps, storing sediments until flushing occurs. Some sediment is discharged when a reservoir is drained to repair the dam. A dam may fail and produce sudden high flows capable of moving large amounts of sediment. In May, 1948, Fred Burr Reservoir failed, releasing a peak flow of about 23,000 cfs. This flow was forceful enough to move large boulders and to significantly degrade the channel. Normally Fred Burr Creek carries a peak flow of about 250 cfs. Channel disturbances also occur if surplus water is dumped into the creeks when diversion ditches exceed their capacity. This abnormal flow regulation results in sediment deposition when flow is diverted from the creek, and subsequent flushing when water is dumped back in. Ditch blowouts can also contribute sediment to the stream system.

In 1890, a mill pond was constructed on the Bitterroot River for the purpose of storing and handling saw logs. The main channel was dammed near

Hamilton from 1890 to 1938 when the dam washed out. This dam undoubtedly altered the sediment flow in the river. Sediment settled out in the quiet water behind the dam, creating accumulations that were flushed out in 1938 when the dam failed.

The population of Ravalli County has nearly doubled in the past 20 years. Residential development involves construction activities that remove vegetation, compact soils, and consequently increase surface runoff. Road systems in housing subdivisions are potential sediment sources especially during initial construction when storms can wash erodable materials into the streams. Housing developments can also reduce the land area capable of absorbing rainfall, and consequently runoff may increase.

River channel stability can be impacted by floodplain development. One form of bank erosion is caused by local mass wasting. Mass wasting may be further aggravated by construction of homes on river banks, operation of equipment on the floodplain adjacent to the banks, added gravitational force resulting from trees, location of roads that may cause unfavorable drainage conditions, saturation of banks by leach fields from septic tanks, and increased infiltration of water into the floodplain as a result of changing land use practices. If the banks become saturated and possibly undercut by the flowing water, blocks of the bank may slump or slide into the channel.

Man-made alterations of the Bitterroot River channel itself lead to accelerated channel instability. Instances in which the channel has been bulldozed to straighten the river's course significantly effect river morphology. Additionally, the impact of bulldozing can destroy fisheries habitats and spawning beds. Haphazard riprapping causes the river to shift in an unplanned fashion. Unless properly designed and placed, bank revetment can be more destructive than beneficial, particularly to the channel adjacent to and

downstream of bank protection works. Often bank protection techniques involving use of car bodies, tires, and other debris simply washes downstream and deposits in undesirable locations. Systematic use of spur dikes or wing walls has been attempted, but without the full cooperation of landowners, such measures have been strikingly unsuccessful.

Effective control of bank erosion will require a basin-wide plan. Bank erosion protection devices installed by individual landowners should satisfy the requirements of such a plan, or be prohibited, if success is to be achieved.

3.6 Water Quality

The major problems currently associated with water quality degradation are caused by irrigation withdrawals and return flows. Irrigation withdrawal problems occur during the summer when reaches of the Bitterroot River are nearly dewatered. Minimum stream flows required to support trout fisheries are not being maintained in several portions of the Bitterroot drainage, particularly in the middle sections of the river. Unnaturally low flows lead to thermal increases and consequent decreases in dissolved oxygen. As water warms, its ability to hold oxygen in solution decreases. Irrigation return flows discharge the required water to the river, however, they also return sediment and nutrients. Increased nutrients in conjunction with elevated water temperatures can create algal blooms. As this organic matter decays, oxygen is used up by microbes that metabolize the debris, further reducing oxygen concentrations. Monitoring data from municipal and industrial sources indicate that dewatering for agricultural purposes has a more adverse effect on water quality in the Bitterroot River than the combined municipal and industrial discharges.

Water quality from the mouth of the river shows increases in nitrate concentrations and coliform bacteria densities. Although the data shows no

violations of water quality standards, it does indicate some deterioration in the water quality. High coliform densities, high nutrient concentrations, and increases in algae populations may result from the entrance of untreated wastes into the river. When septic systems are placed in the coarse alluvium adjacent to the river, sewage may seep laterally into the river. The increase in residential development along the river can result in this sort of contamination. Dense concentrations of livestock along the river also provide a source of bacteria and nutrients. Surface runoff from adjacent feedlots or intensively grazed areas creates pollution problems in the Bitterroot River.

The tributaries to the Bitterroot River are generally of excellent water quality. Increases in suspended sediments occur in the initial period following road construction. However, when roads are properly constructed, their impact on the stream water quality is only temporary. In the past, indiscriminate road building and logging practices degraded the water quality substantially in terms of suspended sediment concentrations.

IV. HYDRAULICS AND RIVER MORPHOLOGY

4.1 Morphology of the Bitterroot River

The hydraulic characteristics of the Bitterroot River describe the movement of water and sediment through the channel. River hydraulics reflect the topography, geology, and climate of the drainage area and influence the river's morphology. The Bitterroot River flows in a relatively stable channel upstream of Hamilton. Between Hamilton and Stevensville, the river exhibits a tendency to braid, dividing into several channels that span a wide area. A braided river is characterized by multiple channels, channel bar formation, a low sinuosity, a high width to depth ratio, a high-bed load, and an erosive behavior of bank attack.

The channel network is altered during peak flows in May and June. Thus, after unusually high peak flows, the channel may become repositioned in a dramatically different location. The magnitude of the peak runoff in the spring season is determined mainly by the volume of accumulated snow and the rapidity of snow melt. Weather conditions such as continued warm spring temperatures and heavy late-spring rainfalls enhance snow melt conditions. Rapid snow melt sends torrents of water rushing down into the Bitterroot River. High springtime flows are characteristic of rivers draining steep, mountainous terrain, and have a tremendous capacity to move sediments.

The glacial alluvium through which the river flows is composed of coarse sediments deposited during past glacial cycles. The riverbed consists mainly of gravel and cobbles. The predominance of large material indicates an armored bottom. The armoring protects the river bed from being degraded and forces the river to spread out during peak flows. Since the river is prevented from deepening its channel, it must widen to accommodate the

increased volume of water. This behavior results in channel bank cutting, as well as new channel and subchannel formation.

During extended periods of low annual peak flows, a river tends to confine itself to fewer channels and exhibits some degree of (apparent) stability. If subsequent flood years occur during relatively short time intervals the increased erosive power of the river cuts more channels to carry the additional flow, and the river strays from its previously defined channel.

By examining annual peak flows for the period of record, trends can be identified and possible causes of accentuated channel shifting can be defined. Data from two gaging stations on the Bitterroot River reveal that peak flows have increased substantially in recent years. From 1930 to 1946 the Bitterroot River flowed in a relatively stable, meandering channel. Evidence implies that this stability was the result of abnormally low peak flows during those years.

4.2 Lane Relation

A useful formula for predicting the river's response to changes in the watershed is the following form of the Lane relation for geomorphic interpretation as identified by Simons and Senturk (1977):

$$Q_w S \propto \frac{Q_s \cdot D_{50}}{C_w}$$

where:

Q_w = water discharge

S = channel slope

Q_s = sediment discharge

D_{50} = median grain diameter of bed material

C_w = concentration of suspended sediments

The existing channel is the product of its interaction with water and sediment flows over a long period of time. If substantial changes in Q_w or Q_s occur, the river gradually adjusts to achieve equilibrium such that neither degradation nor aggradation will occur. This adjustment often requires considerable time, during which erosion and deposition may alternate as the river seeks equilibrium. Changes in the watershed system that result in increased flow, Q_w , will be accompanied by an increase in sediment discharge, Q_s , an increase in median grain size, D_{50} , or a decrease in concentration of suspended sediment in order for the channel to maintain equilibrium. If these changes in Q_s , D_{50} , and C_w do not occur, the energy created by the increased flow will tend to degrade the river channel. As another example, assume that sediment loads from the watershed have increased in the past 50 years or so. Increased sediment loads, Q_s , must be accompanied by an increase in slope or an increase in water discharge, otherwise the channel will aggrade since the flow will not have enough energy to move the increased sediment load. A river can achieve an increase in slope by reducing its meandering. Thus, the above equation is useful in predicting the geomorphic response of a river to changes in water and sediment discharge, changes in alignment and changes in the characteristics of the bed material of the channel.

4.3 Classification of Rivers

A river will develop a characteristic pattern depending upon: the material it flows through, the flow conditions, the sediment load, and vegetative effects. A river channel may be broadly classified as straight, meandering, or braided. Sinuosity is one criterion on which this classification is based and can be expressed as the ratio of the river distance between two points to the straight line distance between those points. A perfectly straight

river has a sinuosity of 1.0, braided usually less than 1.3, and meandering greater than 1.5. A braided stream is one that consists of multiple, intertwining channels separated by bars, and is generally unstable, altering its channel configuration at high flows. Characteristically, it carries large quantities of sediment and tends to be wide and shallow, even with rising and falling flood stages. In general, a braided channel has a relatively steep slope, large bed load, and often only small amounts of silt and clay in the banks. As shown in Figure 29, type of sediment load, sediment size, sediment load (amount), flow velocity, stream power, width-depth ratio, and channel gradient are related to channel pattern and relative stability of alluvial channels.

An armored bed of large cobbles, combined with easily erodible banks, creates channel conditions conducive to braiding. During high flows, the armor layer protects the bed from eroding, forcing the river to widen instead. The erosive energy of the water is transferred to the relatively unstable channel banks, cutting new channels and changing the river's alignment. As the flow decreases, sediments settle and create bars which may stabilize to form vegetated islands.

Braiding is also related to channel slope and water discharge. Besides the tendency to be steep, braided channels carry large volumes of water on an annual basis. When different rivers are plotted with respect to mean annual flow and channel slope those with similar geomorphic characteristics tend to fall into distinct regions of the graph (Figure 30). The Bitterroot River at Missoula has a mean annual flow of close to 2300 cfs and an average slope of 0.0021 throughout its length. Thus, the river plots just above the line separating braided streams from intermediate streams.

Braided portions of a river can be converted to a meandering condition by various means. By lengthening the thalweg and consequently reducing the

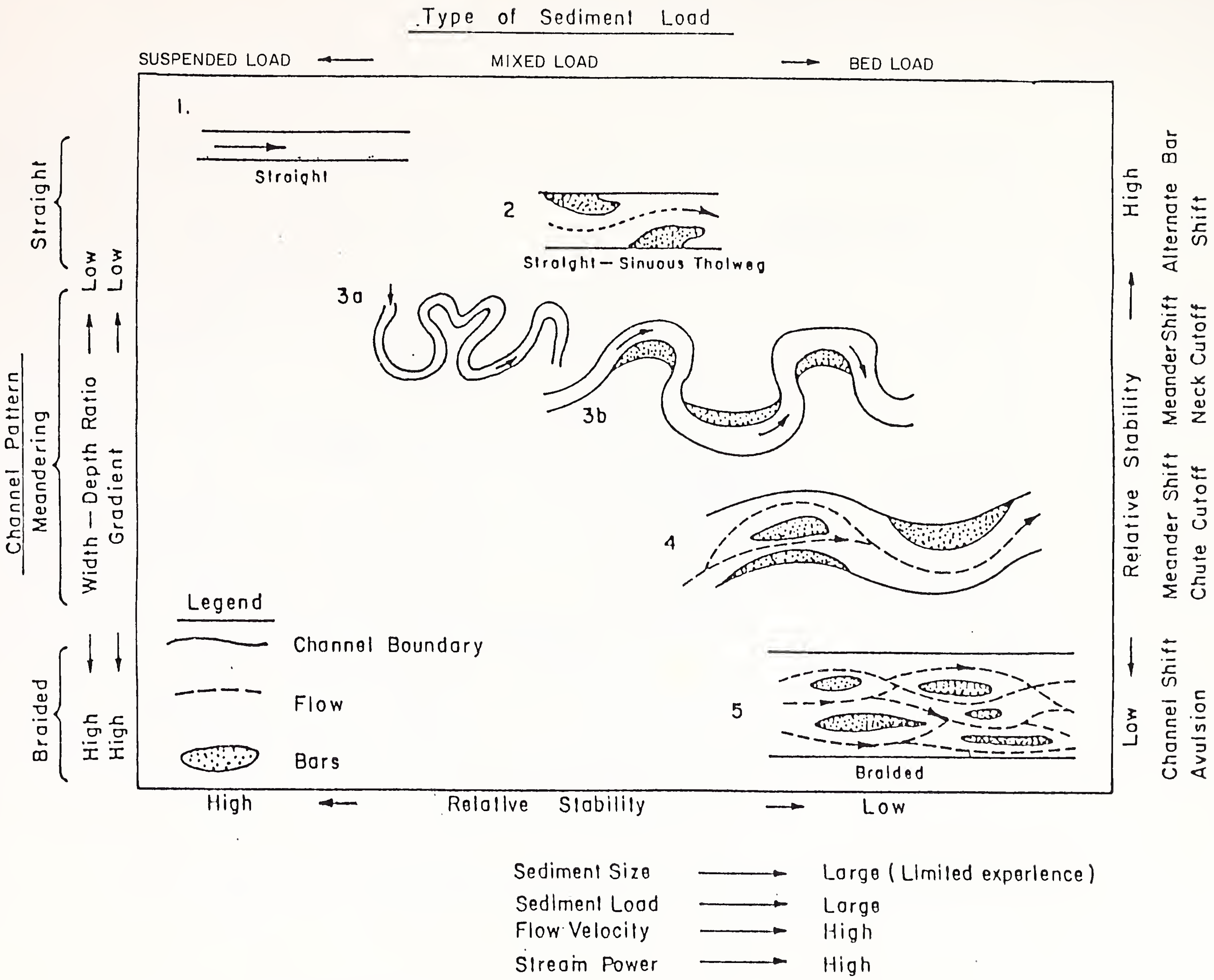


Table 29. Classification and Stability of Alluvial Channels (from Schumm, 1977).

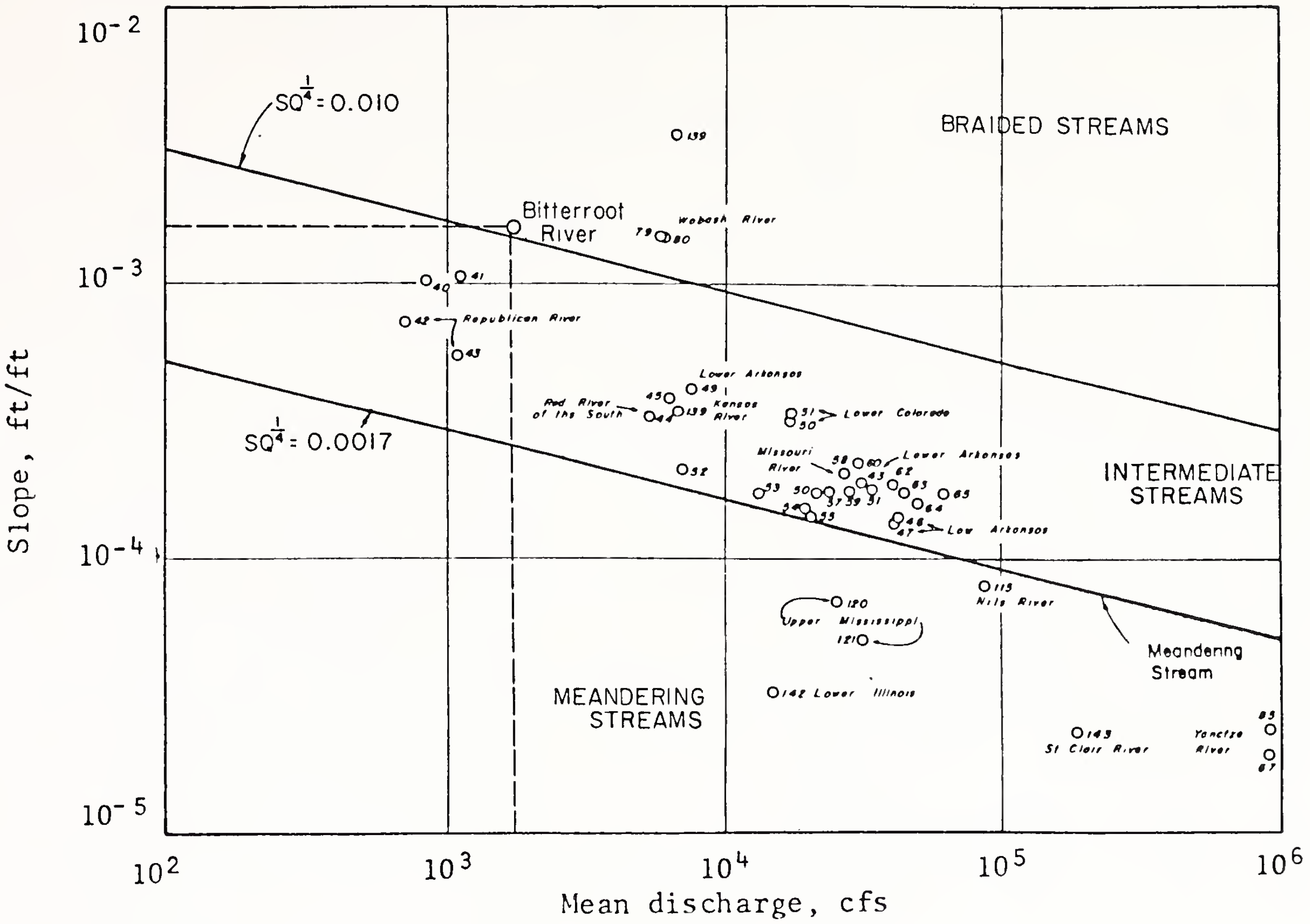


Figure 30. Slope-Discharge Relation for Braiding or Meandering in Sandbed Streams (after Lane, 1957).

channel gradient, the channel could be transformed into a meandering pattern. However, this conversion would require major channelization and structural treatments. The channel gradient could also be reduced by strategically located controls to reduce the channel slope. Another means of manipulating the channel configuration would be to reduce the peak spring flows by increasing upstream storage. The elimination of flood flows would favor establishment of a meandering system.

A meandering channel consists of alternating bends formed by the processes of erosion and deposition. A meandering channel is not static, rather, it gradually forms and destroys bends through both lateral and longitudinal movement. A meandering river is free to shift its location in the alluvium it flows through and to adjust its channel as it migrates through valleys. Yet it alters its geometry in a much more gradual and predictable way than does a braided stream.

4.4 Sediment Analysis

4.4.1 Bitterroot River

An inventory conducted by the USDA (Soil Conservation Service) indicates that the majority of the material composing the bed of the Bitterroot River is coarse (Ganser, et al, 1979). The study categorized 84 percent of the bed sediments between Hamilton and Florence (Reach II) as boulder, rubble, and gravel (Table 7 and Figure 31). The predominance of coarse materials in the bed indicates that most fine sediments entering from tributaries or scoured from the banks are entrained during high flow and flushed through the system. Since spring flows are so large, high velocities in the main channel can be expected to wash any fine sediments downstream. In bank overflow areas, where the water spreads out over the land the quiet water allows sediments to settle on the floodplains.

Table 7. Bitterroot River Bed Material*

Reach	Average Gradient	Rubble/Boulder	Rubble/Boulder	Gravel	Sand/Silt	Mixed
I	0.34%	66%	24%	5%	0%	5%
II	0.20%	25%	43%	16%	3%	13%
III	0.08%	11%	33%	17%	1%	38%

*Streambed materials were classed into the following groups for ease of identification:

Class	Diameter
Rubble/Boulder	3 to 8 inches/greater than 8 inches
Gravel/Rubble	0.1 to 3 inches/3 to 8 inches
Gravel	0.1 to 3 inches
Sand or Silt	less than 0.1 inch
Mixed	composed of sand/silt, plus one or more of the other types

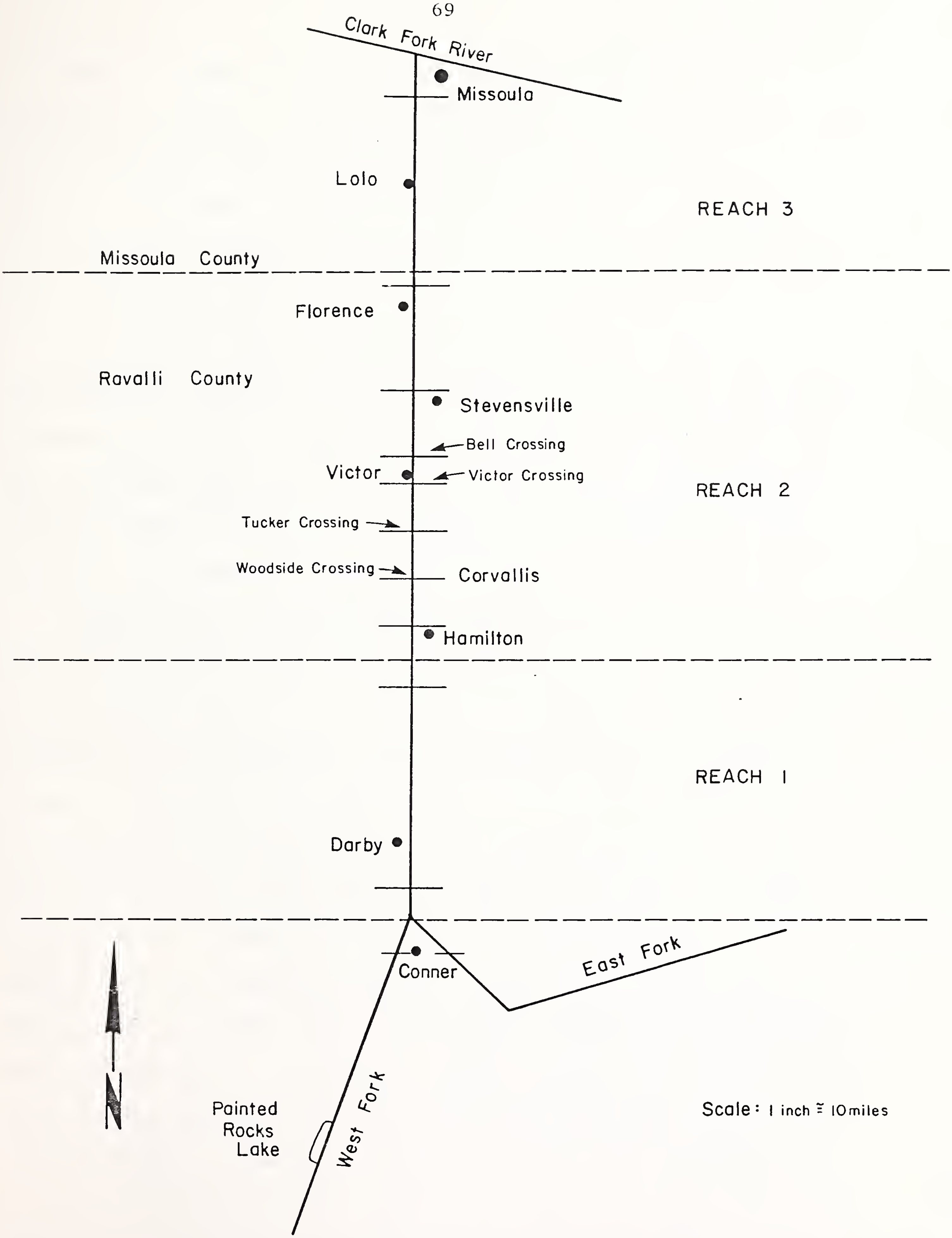


Figure 31. Bitterroot River Reaches, Bridges and Towns.

The U. S. Forest Service has collected data on sediment loads from Bitterroot tributaries. Sediment concentrations tend to be less than 30 mg/l on the average, but have been as high as 440 mg/l in Ambrose Creek. Total annual sediment loads carried by the tributary streams average from approximately 5 to 20 tons/mi^2, but may be as high as 50 to 60 tons/mi^2 according to Bob Hammer, Forest Hydrologist of the Bitterroot National Forest.

Bed loads were also measured in selected east-side tributaries. Bed load consists of materials too heavy to be moved in suspension and refers to sediments that bounce or roll along the stream bed. According to available data, bed loads range from 1 to 6 percent of the total sediment load, indicating that most of the materials transported into the Bitterroot River are relatively fine suspended sediments.

Assuming that all of the sediment carried by the tributaries has dropped out in the Bitterroot River during the past 30 years, an estimate of the depth of the deposited material can be calculated. In order to compute the depth of possible channel aggradation, some assumptions and gross estimates must be made. Assuming that the average annual sediment yield from the Bitterroot River watershed is 50 tons/mi^2 (this value represents some of the higher sediment yields measured in the tributary streams) and that the bulk weight of one cubic foot of sediment is 90 pounds, the space occupied by one ton of sediment would be a maximum of about 22.2 cubic feet. Now an estimate of how many tons of sediment came off the entire watershed during the past 30 years can be computed assuming that: (1) the watershed area is 2800 mi^2 and (2) all of the sediment has settled out in the channel over 30 years. The volume of sediment accumulating in the channel under these conditions is computed to be 9.32×10^7 ft^3. Assuming the total river length from the forks to Missoula is about 100 miles with a mean channel width of 1000 feet,

the area on which sediments would presumably be deposited is 52.8 x 10^7 ft^2, if 9.32 x 10^7 ft^3 of sediments were deposited over this area, and assuming that the sediment covered the channel area to a uniform depth from the merging of the forks downstream to Missoula (the East and West Forks can be considered to be too steep to allow deposition to occur) the depth of aggradation would be 0.18 feet or about two inches. This amount would not produce a noticeable degree of aggradation or change in channel slope. Furthermore, we assumed that all of the sediments carried by the tributaries settled out. It would be more reasonable to assume that since most of the sediments delivered to the river are fine suspended materials rather than coarse bed loads, most of them would be transported downstream by the energy of high spring flows. Visual evidence as well as analysis of bed sediments indicates that this is the case. There was no evidence of sediments building up around trees or bridge pilings. No net aggradation was evident throughout the study reach. Localized aggradation and degradation as the river shifts the coarse bed sediments during high flows. This process creates new channels as old ones are destroyed.

4.4.2 Bed and Bank Material

The ability of a river bank to resist erosion is closely related to the characteristics of the bank material. These characteristics are generally highly variable. Bank material deposited in a river can be broadly classified as cohesive, noncohesive, or stratified. Cohesive material is more resistant to surface erosion and has low permeability that reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. However, such banks when undercut and/or saturated are more likely to fail due to mass wasting processes such as sliding.

Noncohesive bank material tends to be removed grain by grain from the bank line. The rate of particle removal, and hence the rate of bank erosion,

is affected by factors such as: 1) the direction and magnitude of the velocity adjacent to the bank and its turbulent fluctuations, 2) the magnitude and fluctuations in the shear stress exerted on the banks, 3) seepage force, and 4) piping and wave forces. Many of these factors may act concurrently.

Stratified banks are very common on alluvial rivers like the Bitterroot and generally are the product of past transport and deposition of sediment by the river. Thus, these types of banks consist of layers of materials of various sizes, permeability, and cohesiveness. The layers of noncohesive material are subject to surface erosion, but may be partly protected by adjacent layers of cohesive material. This type of bank is also vulnerable to erosion and sliding as a consequence of subsurface flows and piping.

Of the various sediment properties, size has the greatest significance to the hydraulic engineer, not only because size is the most readily measured property, but also because other properties such as shape and specific gravity tend to vary with particle size. In fact, particle size is often sufficient to describe the sediment particle.

Particle size may be defined by volume, diameter, weight, fall velocity, sieve size, and by intercepts through the particle. With the exception of volume, the definitions are generally influenced by the shape and density of the particle.

Size may be measured by calipers, optical methods, photographic methods, sieving, or sedimentation methods. The size of an individual particle is not of primary importance in river mechanics or sedimentation studies, but the size distribution of the sediment that forms the bed and banks of a stream is significant.

Bitterroot River bed and bank materials were analyzed to determine relative size differences. Median grain size (D_{50}) of bed materials decreases

with increased downstream distance (Figure 32). The median grain diameter is the size for which half of the grains are larger and half smaller than this value, and is referred to as the D_{50}. The graph is based on data collected by a visual inspection method on sediment bars at the five locations indicated in Figure 32 (Cartier, 1980). Since the visual inspection method generally determines sizes larger than the actual bed material, the curve fit between these data points designates the upper limit of the D_{50}. It is assumed that a curve 25 percent below the upper curve represents the lower limit of the D_{50} at a specified location. An equation has been developed relating the decrease in D_{50} to downstream channel distance, X. The upper curve was fit to the data points using least squared regression techniques and assuming the relationship of $D_{50_x} = D_{50_{x=0}} * e^{AX}$, where e is the natural base and A is the coefficient to be determined by the regression analysis. The equation describing the curve was determined to be $D_{50} = 122.1 * e^{(-0.02X)}$ where D_{50_x} is the median sediment size in the channel bed at a river distance X downstream from the forks. Therefore, based on this graph, the median grain size (D_{50}) of bed material at Hamilton would be expected to be between about 33 and 49 mm. The bed diameter sizes represent sediments technically classified as coarse gravel (16-32 mm), very coarse gravel (32-64 mm) and small cobbles (64-128 mm) (Table 8). Hence, we may conclude that the majority of the materials composing the Bitterroot River channel bed are gravels and cobbles. This analysis agrees with the results of the Bitterroot River Inventory (Ganser et al, 1979) which estimated the majority of the bed materials as gravel, rubble (cobble), and boulder (see Table 7).

Bed material sizes were analyzed at five sites between Hamilton and Victor using a grid system. The grid, 2 ft x 2 ft with 0.1 ft intervals between grid lines, allows particles to be counted and categorized into

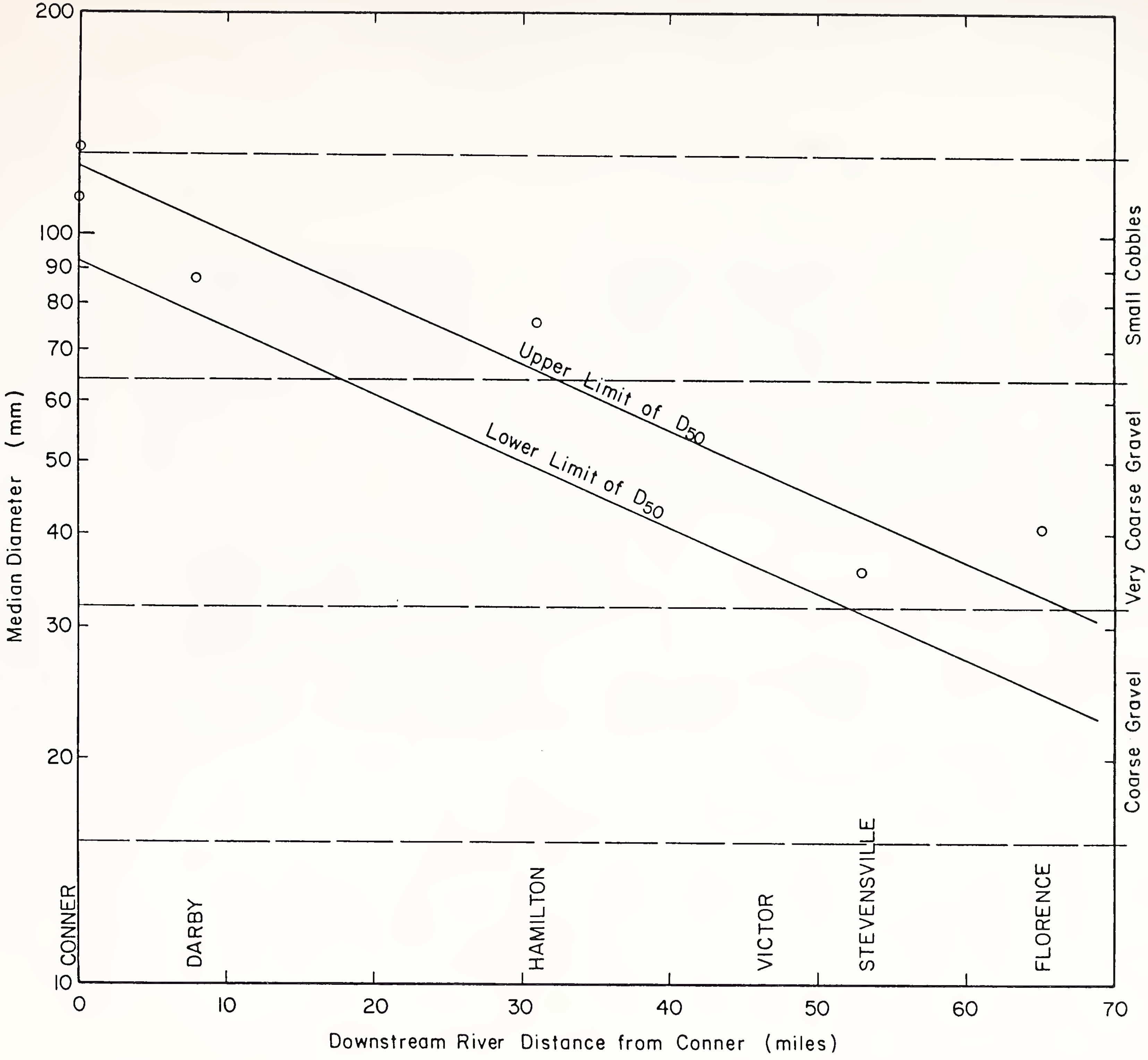


Figure 32. Bitterroot Streambed Armoring Based on Data from Cartier, 1980.

Table 8. Grade Scale of Sediment Particle Sizes

Soil textural class	Large sizes	
	Metric unit	English unit
	Millimeters	*Inches*
Very large boulders	4096–2048	160–80
Large boulders	2048–1024	80–40
Medium boulders	1024–512	40–20
Small boulders	512–256	20–10
Large cobbles	256–128	10–5
Small cobbles	128–64	5–2.5
Very coarse gravel	64–32	2.5–1.3
Coarse gravel	32–16	1.3–0.6
Medium gravel	16–8	0.6–0.3
Fine gravel	8–4	0.3–0.16
Very fine gravel	4–2	0.16–0.08
	Small sizes	
	Metric units	
	Millimeters	*Microns*
Very coarse sand	2.000–1.000	2000–1000
Coarse sand	1.000–0.500	1000–500
Medium sand	0.500–0.250	500–250
Fine sand	0.250–0.125	250–125
Very fine sand	0.125–0.062	125–62
Coarse silt	0.062–0.031	62–31
Medium silt	0.031–0.016	31–16
Fine silt	0.016–0.008	16–8
Very fine silt	0.008–0.004	8–4
Coarse clay size	0.004–0.0020	4–2
Medium clay size	0.0020–0.0010	2–1
Fine clay size	0.0010–0.0005	1–0.5
Very fine clay size	0.0005–0.00024	0.5–0.24

Source: Lane (1947)

different size classes to obtain a plot of size frequency distribution at each site (Figure 33). Results from the grid analysis were not adjusted to be equivalent to a sieve analysis since approximate values will suffice in this case. Average values were then computed for the D_{90}, D_{75}, D_{50}, and D_{35} using the data from all five sites (Figure 34) (for example, the average D_{90} of 107 mm implies that 90 percent of the bed sediments are less than 107 mm in diameter). The D_{50} of 45 mm is consistent with Cartier's data (1980) which indicate that the D_{50} between Hamilton and Victor is somewhere between 40 and 55 mm (Figure 32). The size distribution analysis again reveals that most of the bed sediments are coarse gravels and small cobbles.

Bank materials at two locations were analyzed by the sieving method to see how the median grain size of bank sediment compared to that of bed material. The bank sediment appeared to be considerably finer than bed sediment. Analyses of sediment size distributions were conducted at Victor and Bell Crossing (Figures 35 and 36). The sieve analysis determined the D_{50} of the bank sediment at Victor Crossing to be 0.26 mm, which is classified as medium sand. Sizes ranged from 0.07 mm to 6 mm (very fine sand to fine gravel). At Bell Crossing the D_{50} was 13.3 mm or medium gravel, while sizes ranged from 0.2 mm to 26 mm (fine sand to coarse gravel). The bed and bank sediment size analyses indicate that bank materials tend to be sands and gravels, while bed materials consist mainly of coarse gravels and cobbles.

The banks consist of alluvial material deposited by the river over a long period of geologic history. Approximately forty feet of this sediment was deposited during the glaciation of the Quarternary Period, and much of it is coarse glacial debris from the Bitterroot Mountains. This material

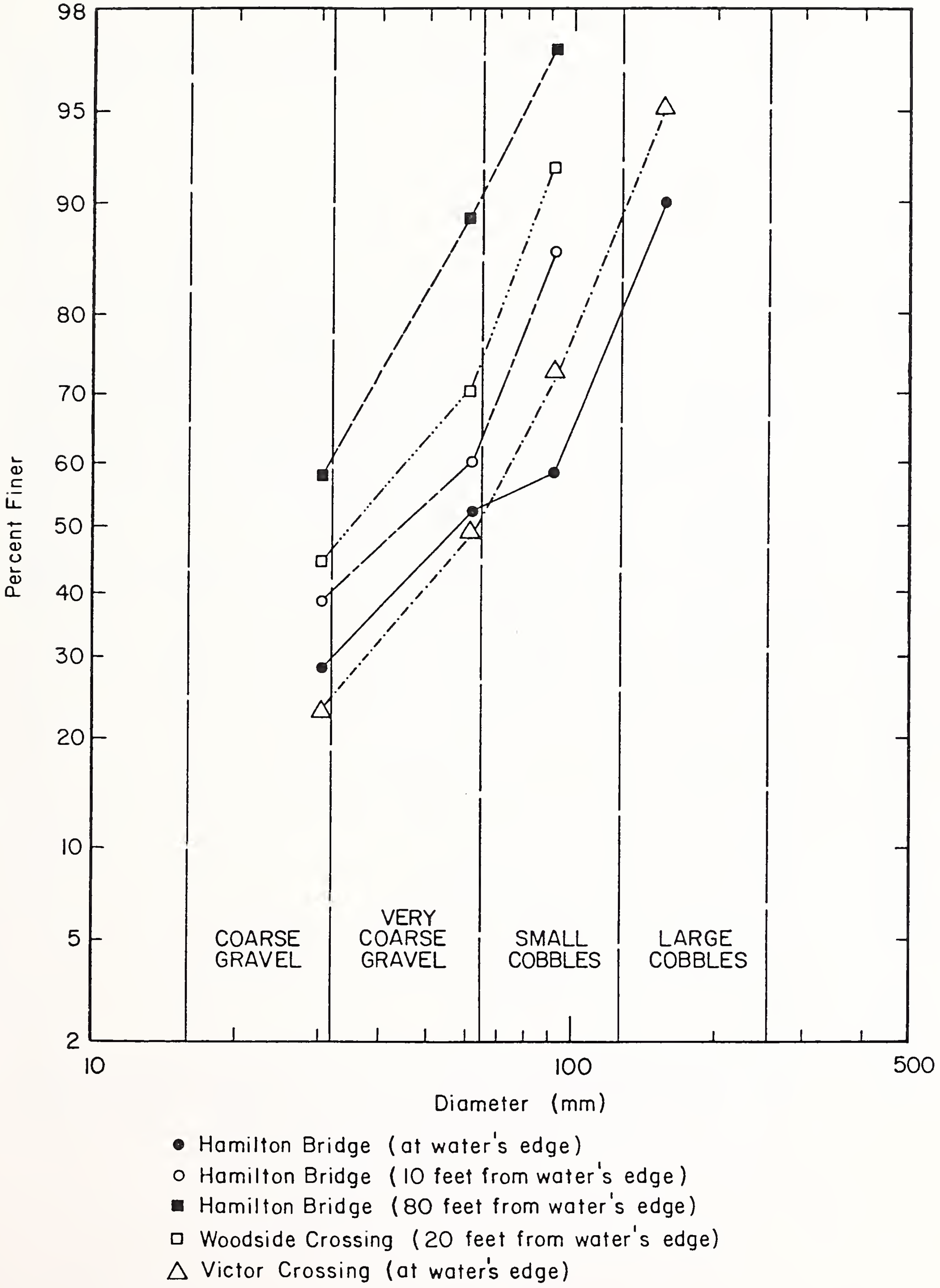


Figure 33. Bed Size Distribution at Bridge Crossings: Grid Analysis.

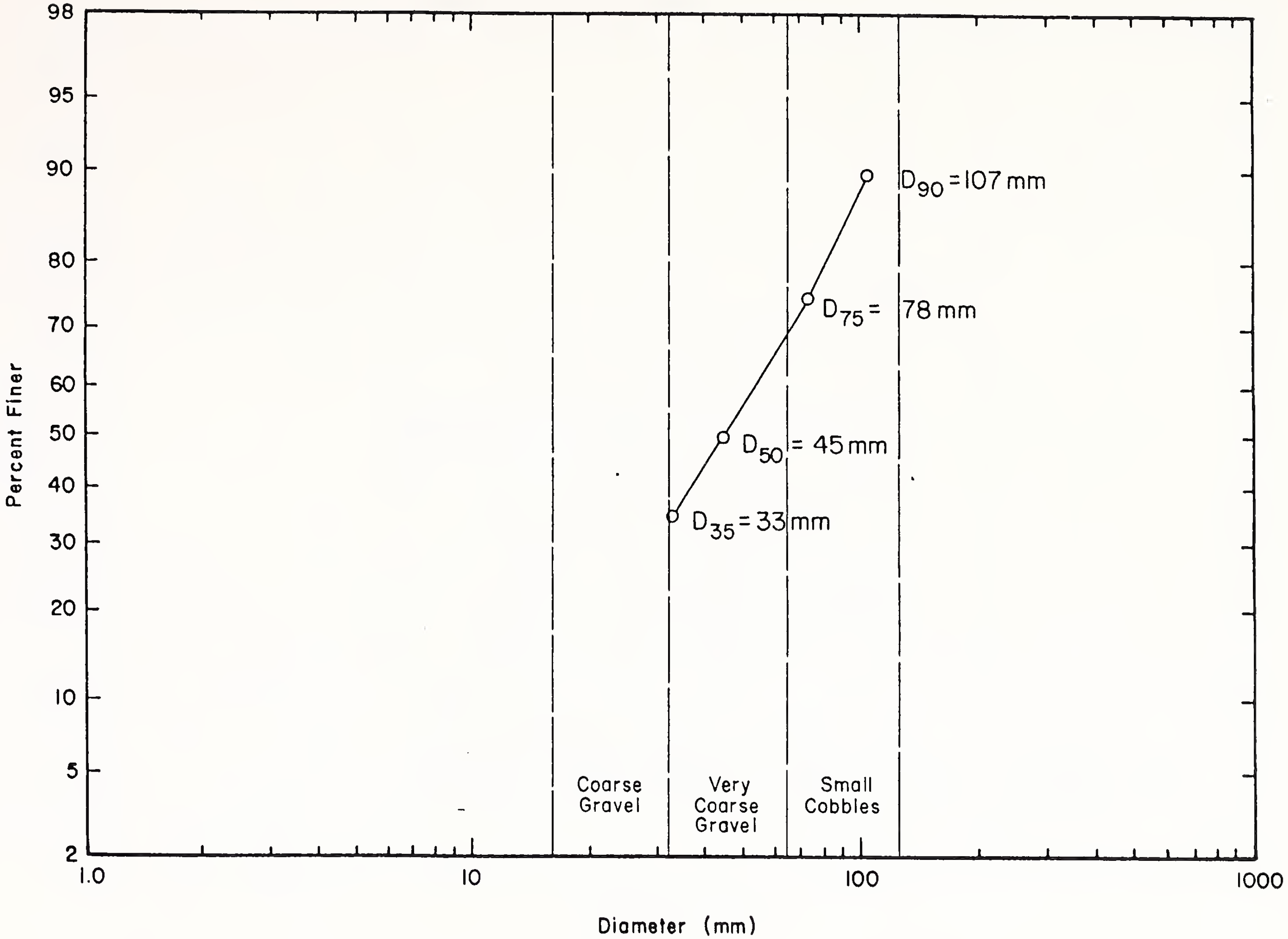


Figure 34. Average Bitterroot River Bed Material Size Distribution: Hamilton to Victor.

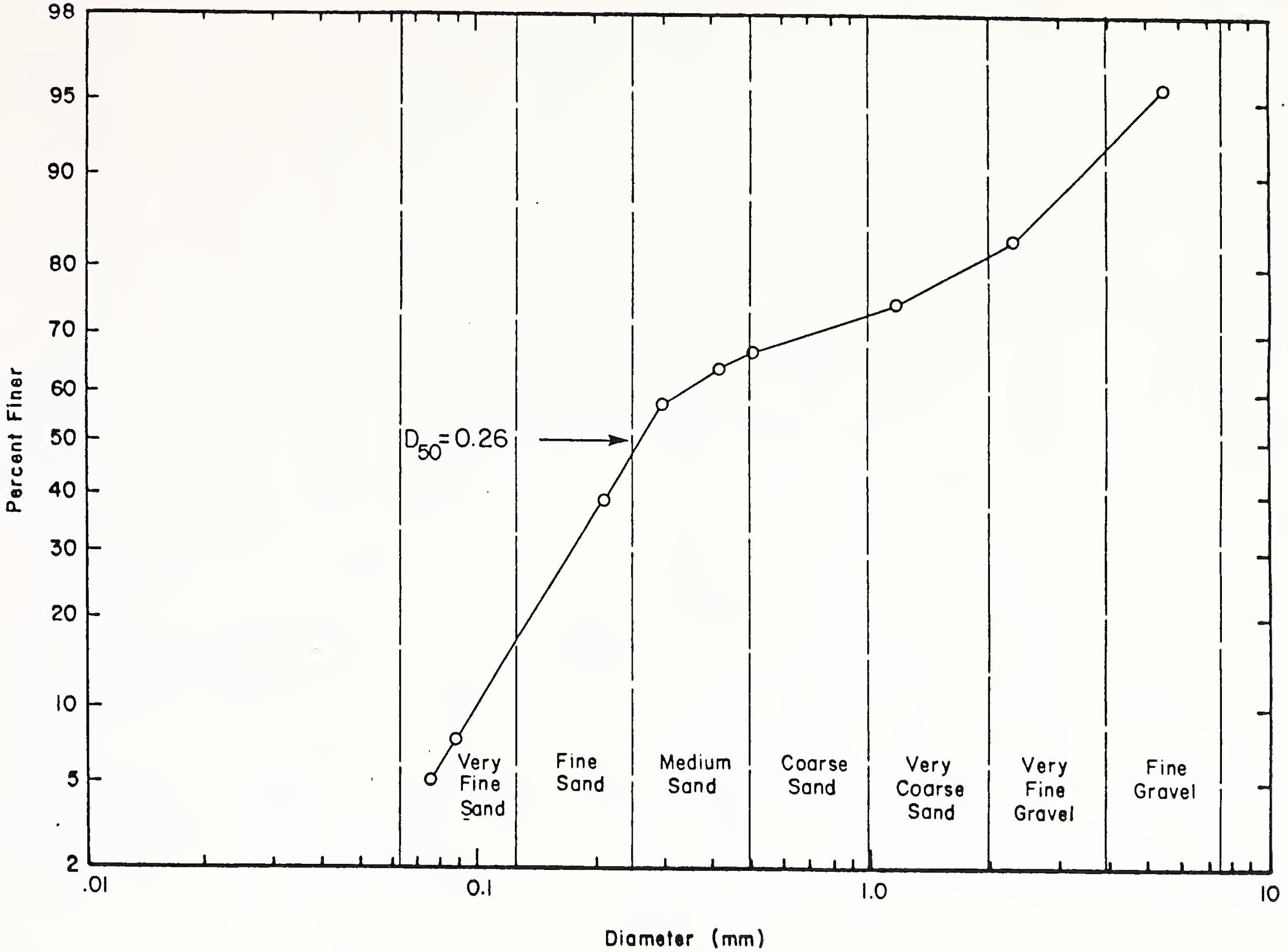


Figure 35. Bank Sediment Size Distribution at Victor Crossing.

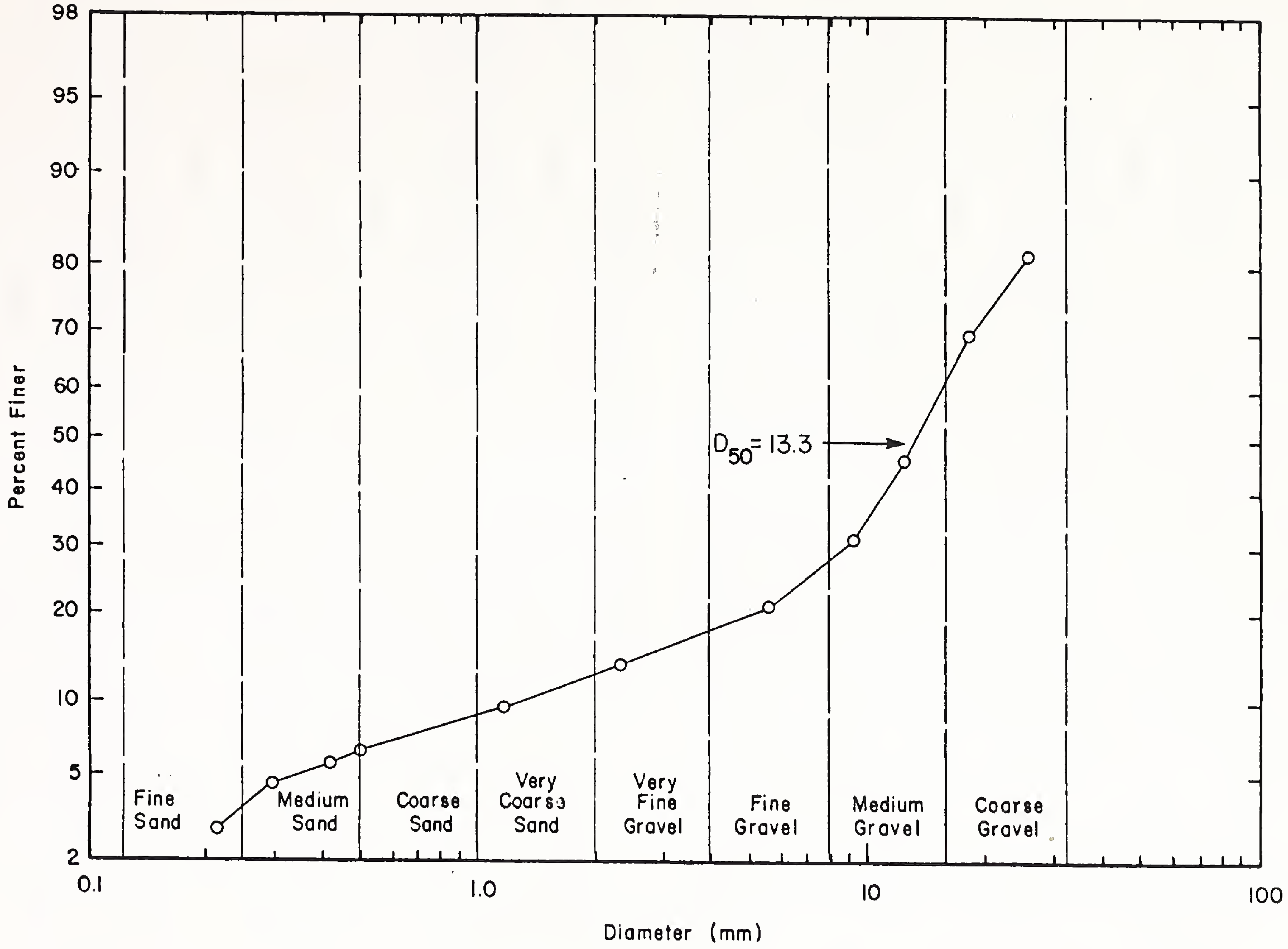


Figure 36. Bank Sediment Size Distribution at Bell Crossing.

was deposited in a wide variety of environments including lake, river, and glacial melt conditions. Hence, various sediment types overlap and intergrade, both laterally and vertically, creating stratified banks. The variability of the sediment layers can be seen in the banks along the channel. A depth of cobble sediments was observed over a layer of finer sands and gravels. This variability in deposits is related to the changing position of the river throughout geologic history. For example, when a given bank site was part of the floodplain, fine sediments were deposited as the river overflowed its banks and quiet water covered the adjacent land. This process created layers of finer sediments. As the river moved laterally toward the bank site, this location became part of the main river bed. With the greater transport capacity of the river channel coarse materials were transported and deposited. Thus, the overlying layer of cobble developed.

4.4.3 Size of Sediment Transported by Tributaries

The size of materials composing the beds of the tributaries and the size of sediments being delivered to the Bitterroot River were also considered. Visual inspection indicates that the west-side tributary stream beds consist of cobbles in the lower gradients and bedrock in the steeper reaches. The cobbles provide an armoring that protects the stream bed from eroding during high flows and enhances river bed stability. Thus, sediment loads are derived from the banks or from the land surface.

The east-side tributaries generally flow over more gently sloping terrain with deeper soils. For example, where Ambrose Creek flows through a somewhat swampy area, its bed is composed of erodible silts that could wash into the Bitterroot River under high flow conditions. An analysis was conducted to determine the size distribution of sediments entering the Bitterroot River at the mouths of the tributaries. As water from a tributary enters the river

its velocity decreases and some of the sediments that it was carrying drop out. Samples of this deposition were collected south of Stevensville at the mouths of Big Creek, and Spring Irrigation Return Flows #1 and #2. The samples were analyzed by the sieve method to determine the sediment size distributions (Figures 37 through 39). The D_{50} sediment size collected at Big Creek and Spring Irrigation Return #1 and #2 were 8.6 mm (fine gravel), 0.48 mm (medium sand), and 15.9 mm (medium gravel) respectively. According to Figure 32, the D_{50} of the bed at these approximate locations is somewhere between 32 and 43 mm (very coarse gravel). Therefore, we conclude that sediments delivered to the river by tributaries and irrigation return flows are substantially finer than those composing the river bed.

In summary, the fine sediments entering the river from the banks and tributaries appear to be washed on downstream, rather than settling out in the bed. Any coarse sediments carried down by the tributaries and actually deposited in the river represent an insignificant amount compared to the volume of sediment available in the natural alluvial river bed. The great depths of glacially deposited sands, gravels, and cobbles through which the river flows provide an abundant source of sediments which are constantly shifted back and forth across the channel during high flows. The illusion of aggradation may result from this process, but if cross-sectional profiles were taken along the channel's length, incidences of channel deepening would be expected to equal those of channel filling. No net aggradation appears to be occurring.

4.5 Movement of Bitterroot River Bed Sediments at Darby and Bell Crossing

The movement of bed material in an alluvial river is related to the bed configuration. Bed configuration is defined as all irregularities larger than the largest particle size forming the bed. Bed geometry, bed form and

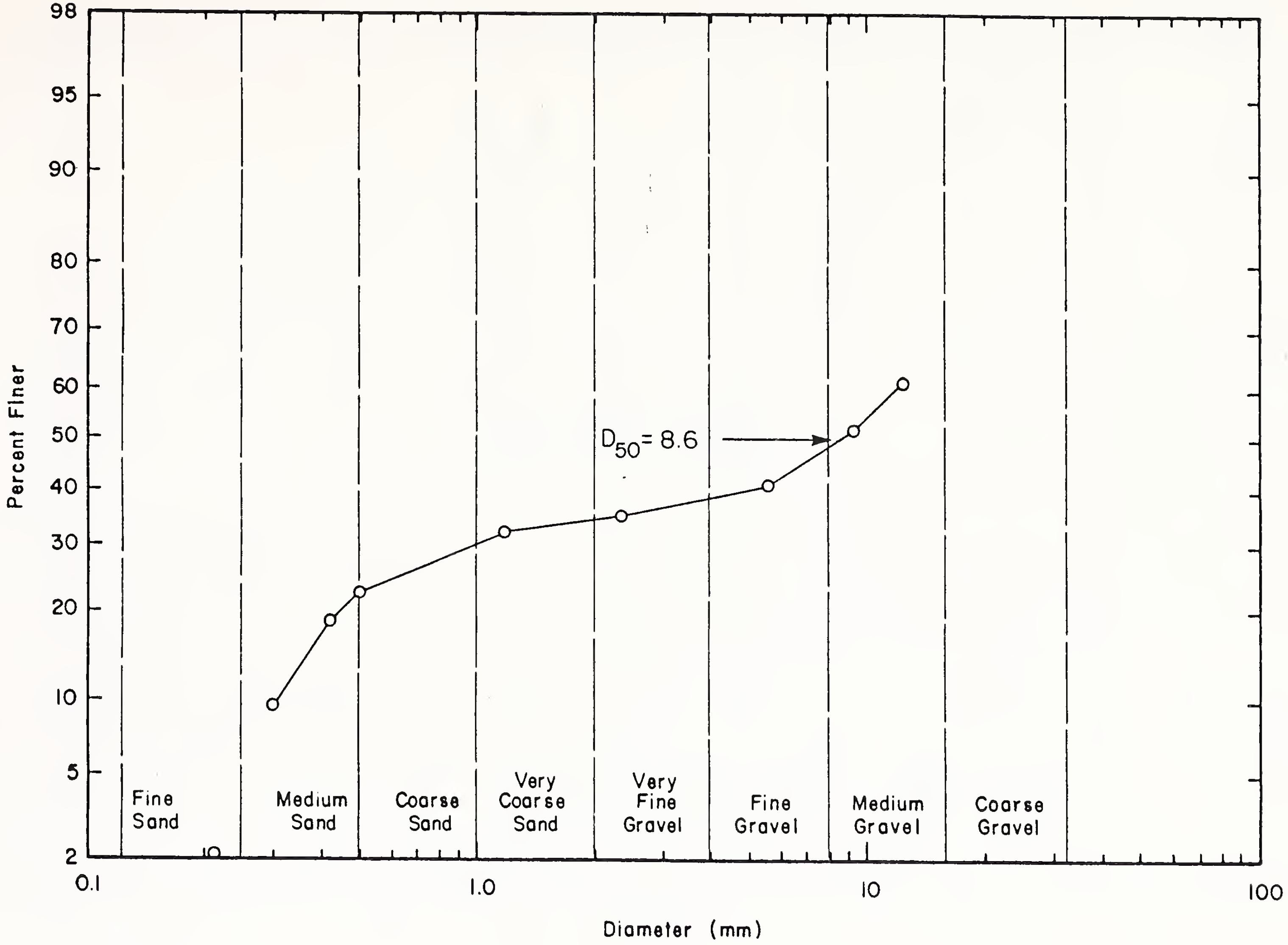


Figure 37. Distribution of Sediment Delivered to Bitterroot River by Big Creek.

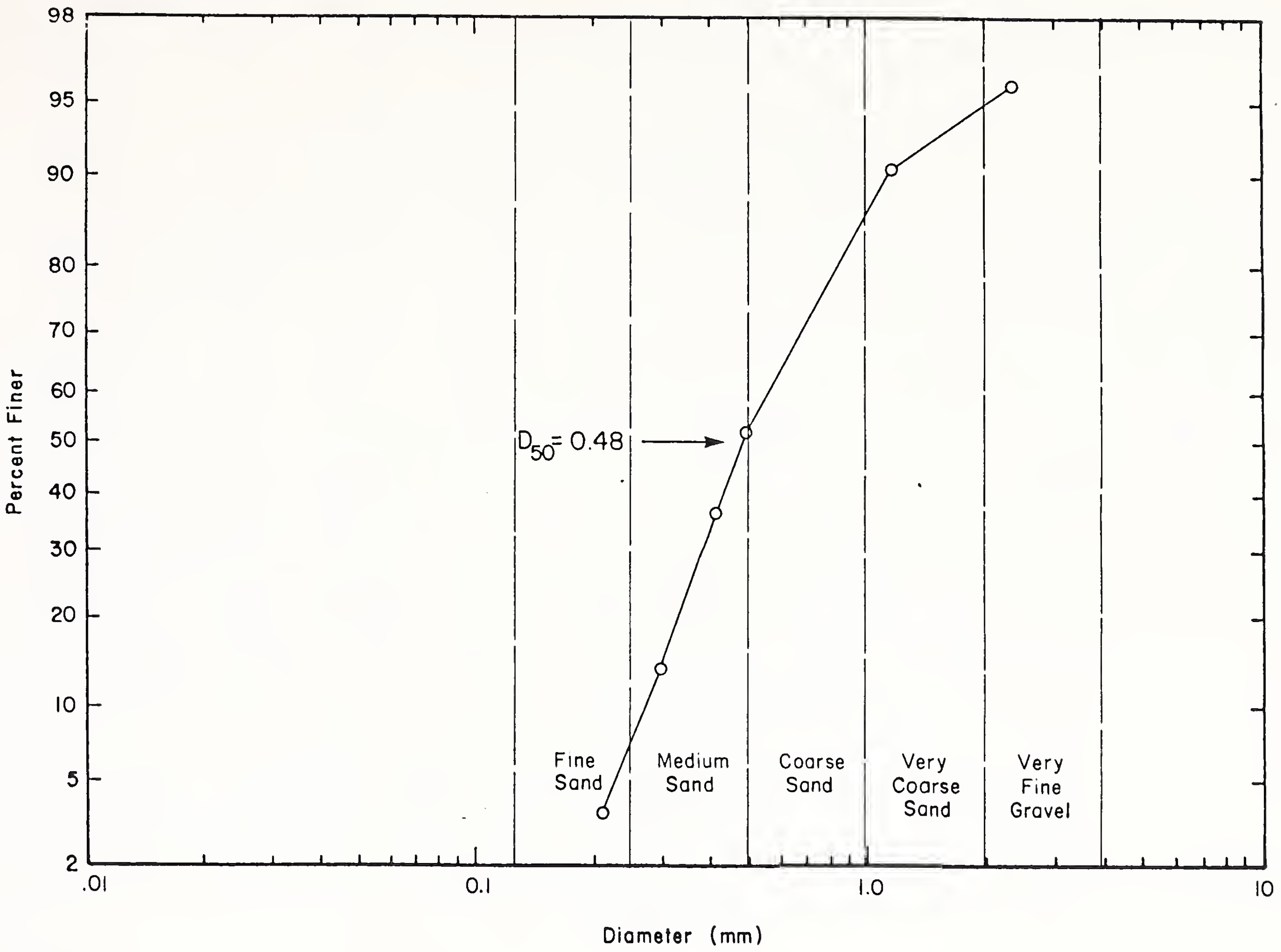


Figure 38. Size Distribution of Sediment Delivered to Bitterroot River by Spring Irrigation Return Flow #1 (South of Stevensville).

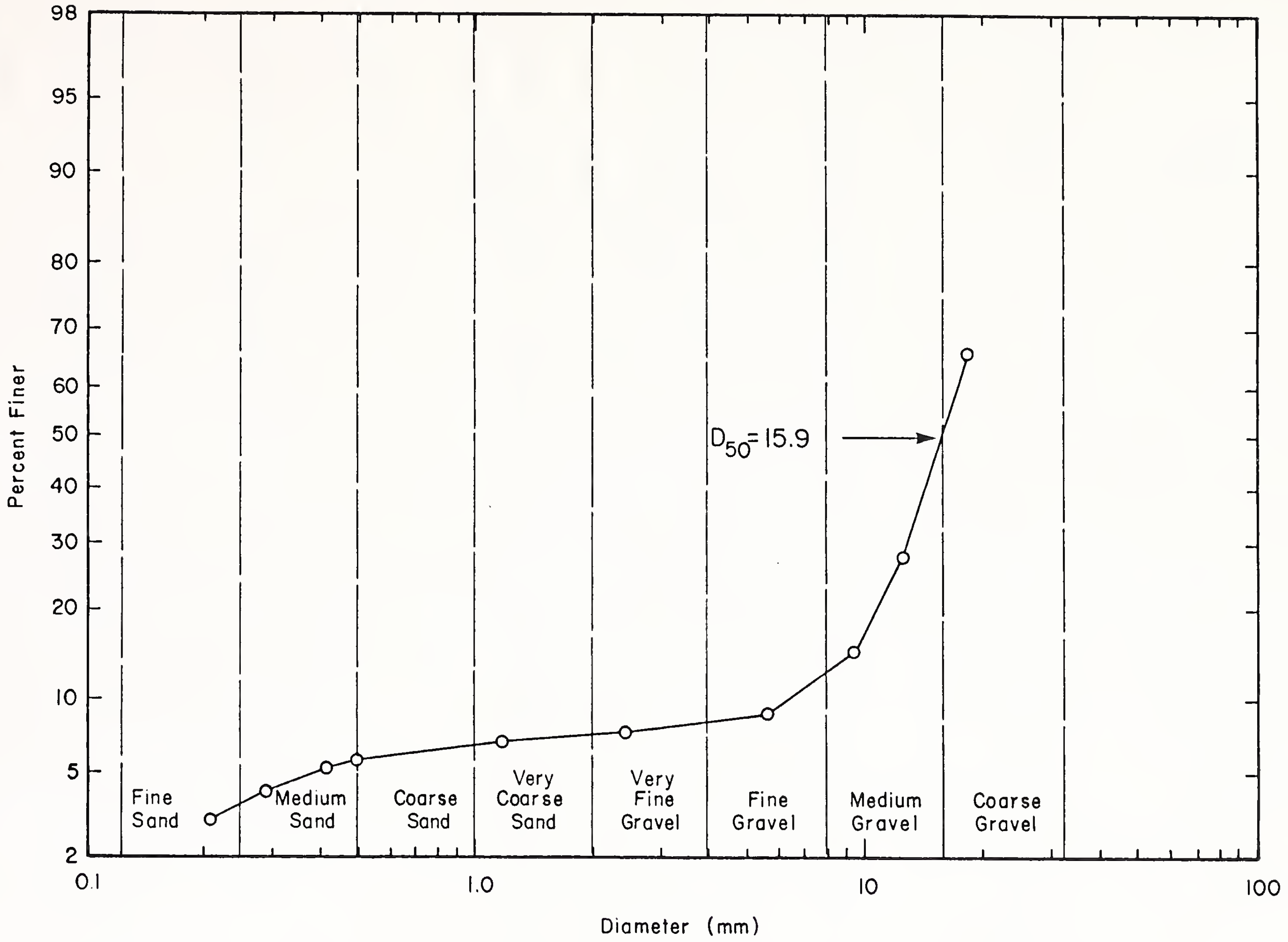


Figure 39. Size Distribution of Sediment Delivered to Bitterroot River by Spring Irrigation Return #2 (South of Stevensville).

bed shape are common synonyms for bed configuration. Bed configurations range from small ripples to large sand and gravel bars. These roughness elements affect resistance to flow, velocity, and velocity distribution, and hence have an important effect on bank erosion. As cited before, the accumulation of bed sediment in the form of bars causes a displacement of flow. For example, the forming of an alternate bar adjacent to one bank forces the water towards the opposite bank, increasing the velocity of flow and the shear stress attacking the bank. These alternate bars form in all straight and relatively straight reaches of alluvial rivers where transport of bed material occurs.

The maximum particle size that a particular flow is capable of moving can be determined for a specific site. The following analysis determines the relationship between flow and sizes of materials set into motion at two different sites: (1) Bitterroot River near Darby, and (2) Bitterroot River above Bell Crossing. This analysis indicates the sediment sizes that can be expected to flush through the system, and explains why the sediments composing the river bed are so coarse.

4.5.1 Shields' Relation

An evaluation of relative stability can be made by evaluating the incipient motion parameters. The definition of incipient motion is based on the critical or threshold condition under which the hydrodynamic forces acting on the sediment particle are such that, if increased even slightly, they would move the particle. Under critical conditions, or at incipient motion, the hydrodynamic forces acting on the grain are just balanced by the resisting forces of the particle.

In general, Shields' relation (Figure 40) is adequate to define beginning of bed material motion. In this figure the dimensionless shear stress F_* represented by

$$F_* = \frac{\tau}{(\gamma_s - \gamma)D}$$

where τ is the shear on the bed, γ_s is the unit weight of sediment, γ is unit weight of water, and D is particle size and is related to the boundary Reynolds number R_* as

$$R_* = \frac{U_* D}{\nu}$$

where U_* is the shear velocity and ν is the kinematic viscosity of water. The curve essentially represents the critical shear stress, τ_c , to put a particle of diameter, D , into motion under the conditions defined by R_* and F_* . F_* is relatively constant when $R_* > 70$. The solution of τ_c is obtained in this region of the curve using $F_* = 0.047$ from the graph.

Therefore, $\tau_c/(\gamma_s - \gamma)D = 0.047$ and the critical shear stress (τ_c) required to put a given particle diameter (D) into incipient motion can be evaluated. The velocity, V_c , corresponding to this τ_c is computed using the relation:

$$V_c^2 = \frac{8\tau_c}{f_\rho}$$

where f is the friction factor accounting for resistance to flow created by the bed and bank, and ρ is the density of water (1.9 $\text{lb-sec}^2\text{-ft}^{-4}$). Applying this procedure for several particle diameters allows defining a relationship relating the discharge (or velocity) required to transport sediments of various diameters.

The Darcy-Weisbach friction factor, f , must be determined based on the particular channel characteristics. This factor is related to Manning's

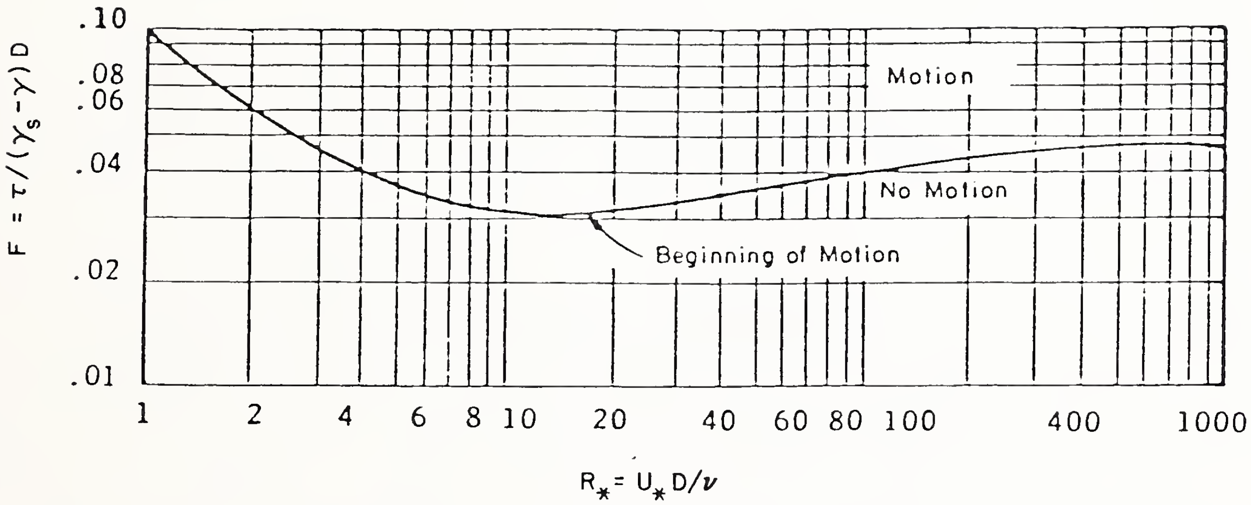


Figure 40. Shields' relation for beginning of motion (adapted from Gessler, 1971).

n , which is a roughness factor and is also a measure of resistance to flow. Manning's n is used in the Manning equation to determine velocity:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

where R is the hydraulic radius (approximately equal to the flow depth in a wide river), and S is the slope of the energy gradient (approximately equal to bed slope under uniform flow conditions).

4.5.2 Calculation Procedure

The nearest available channel characteristics and flows were for the Bitterroot River near Darby, therefore these were used in the calculation. To determine a representative value for the channel roughness, different estimates of n were evaluated.

The U.S. Geological Survey measured the roughness factor, n , at the West Fork of the Bitterroot River near Conner as n = 0.036 . Downstream at Darby, the roughness would be expected to be less since channel banks offer less effective resistance in a wider reach. Another way to determine n compares the appearance of the river channel in question to a channel having a measured roughness factor (Chow, 1959). By the comparison method, the Bitterroot River at Darby has an estimated n value of 0.026. A third method is to compute n from the Manning equation, using hydraulic radius and velocity relationships from Figure 41. A value of 0.0035 for the bed slope was obtained from Figure 42. Assuming that uniform flow conditions exist at all flow values from 100 to 5,000 cfs, it can be assumed that S remains constant at 0.0035. Using the values of R , V , and S from Figures 39 and 40, n was computed from the Manning equation under three flow conditions (Table 9).

An average $\overline{n}$ value of 0.031 was determined to be an adequate estimate

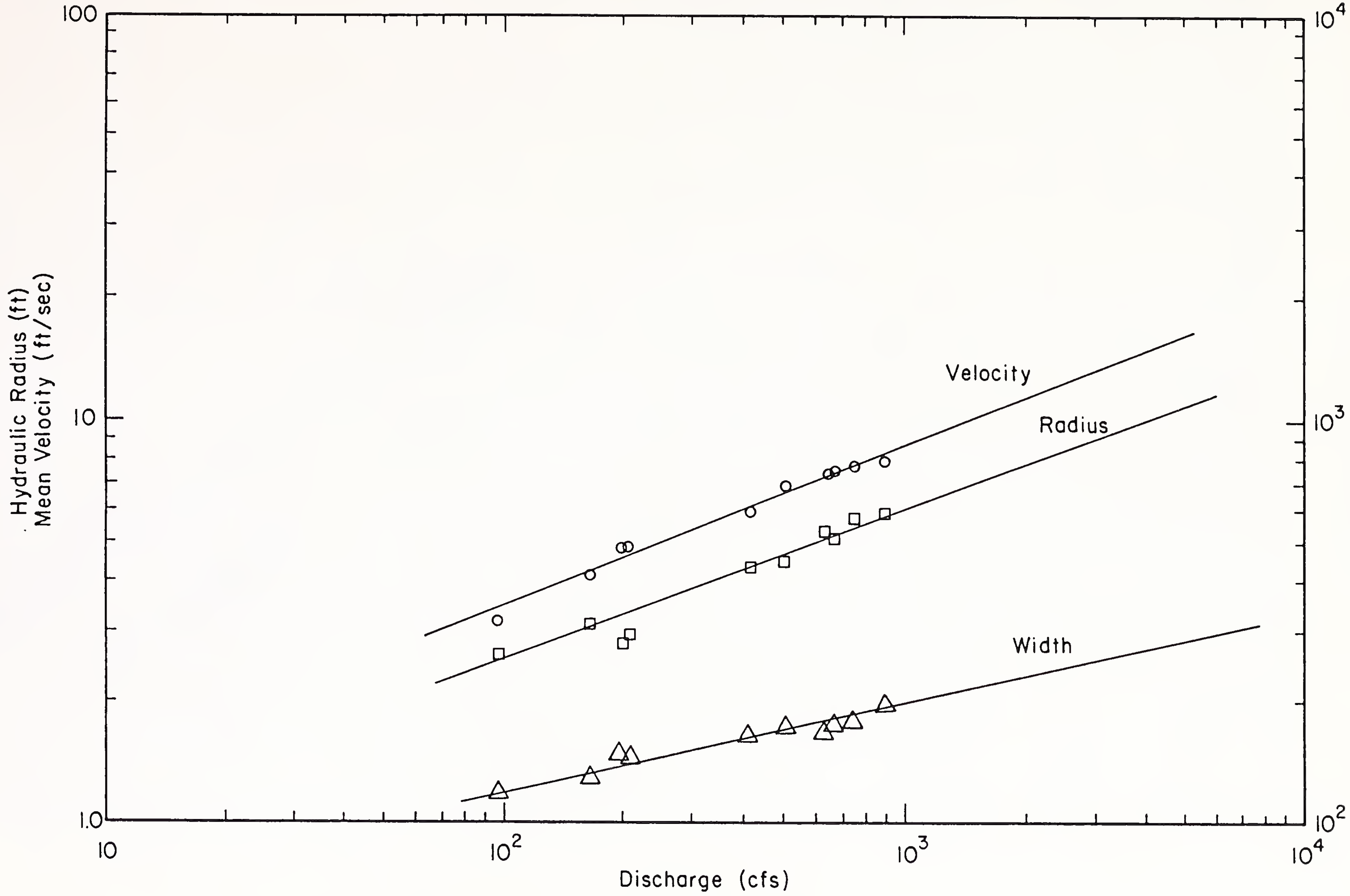


Figure 41. Hydraulic Parameters Bitterroot River at Darby USGS Station
From: Cartier 1980.

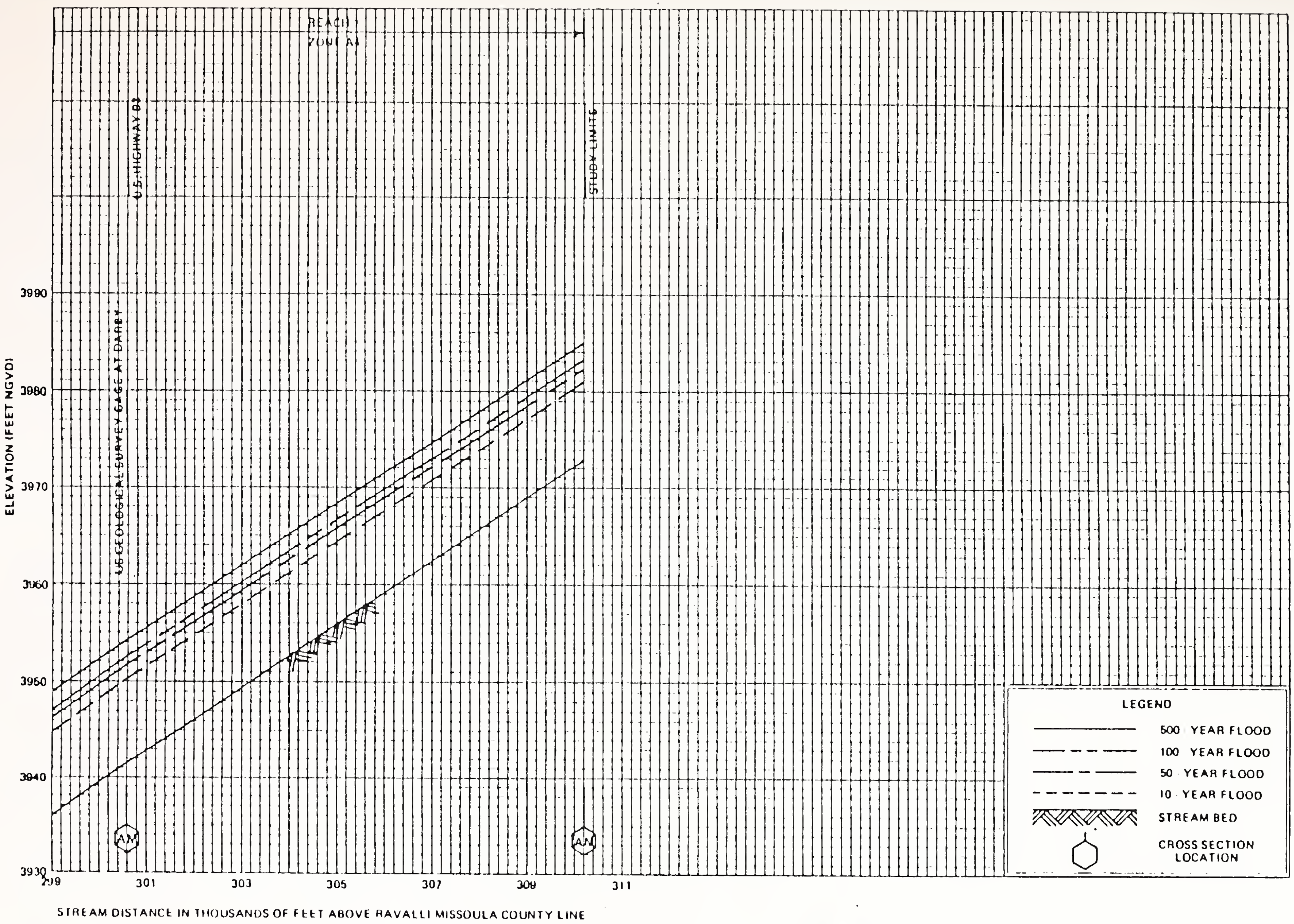


Figure 42. Bitterroot River Profile Near Darby (from FEMA, 1980).

Table 9. Computing Roughness and Friction Factors

Q	R	V	S	N	C	f
Flow (ft^3/sec)	Hydraulic Radius (ft)	Velocity (ft/sec)	Slope of Energy Gradient (ft/ft)	Manning's Roughness Factor	Chezy Roughness Coefficient	Darcy Friction Factor
600	5.0	7.0	0.0035	0.037	52.9	.092
2000	8.0	12.0	0.0035	0.029	71.7	.050
5000	11.0	16.0	0.0035	0.027	81.5	.039
				$\bar{n}$=0.031		$\bar{f}$=0.06

of the roughness factor of the river channel at Darby, based on the above calculations. Using the representative n value(s) the friction factor, f , required computation of the velocity corresponding to the critical shear stress, τ_c . This can be determined from the following two equations:

$$C = \frac{V}{\sqrt{RS}}$$

$$f = \frac{8\gamma}{C^2 \rho}$$

where C is the Chezy roughness coefficient, f is the Darcy-Weisbach friction factor, and V , R , S , γ , and ρ are as previously defined. The final value used as the friction factor was an average value, $\bar{f} = 0.06$ (Table 9).

In summary, critical shear stress values are computed for a range of particle diameters, using Shields' relation. The Darcy-Weisbach friction factor, f , is then computed for the particular channel. The velocity corresponding to the critical shear stress for a given grain size is computed:

$$V_c^2 = \frac{8\tau_c}{f\rho}$$

After computing V_c , the corresponding Q_c is taken from Figure 41. Table 10 summarizes the critical values to initiate movement for a range of particle sizes. We now know the flow required to put various sized bed materials into incipient motion. From this relation (Figure 43), we can see that bed materials over 10 inches in diameter will be in motion only for flows greater than 5,000 cfs. Such high flows occur for only a short period during May and June.

A similar analysis was conducted for the Bitterroot River above Bell Crossing. This section of the river flows in a wide, braided channel, while the channel at the Darby site is much narrower and deeper. Figures

Table 10. Determining Flow to Set Particle Sizes into Incipient Motion

D Diameter of Particle		Texture Class	τ_c Critical Shear Stress (lb/ft^2)	V_c Velocity (ft/sec)	Q_c Darby Site (ft^3/sec)	Q_c Bell Crossing Site (ft^3/sec)
ft	inches					
0.01	0.12	Fine Gravel	0.048	1.82	20	100
0.1	1.2	Coarse Gravel	0.48	5.74	340	7,000
0.2	2.4	Very Coarse Gravel	0.97	8.16	800	25,000
0.4	4.8	Small Cobble	1.94	11.55	1700	--
0.7	8.4	Large Cobble	3.39	15.26	4000	--
1.0	12.0	Small Boulder	4.85	18.26	7000	--

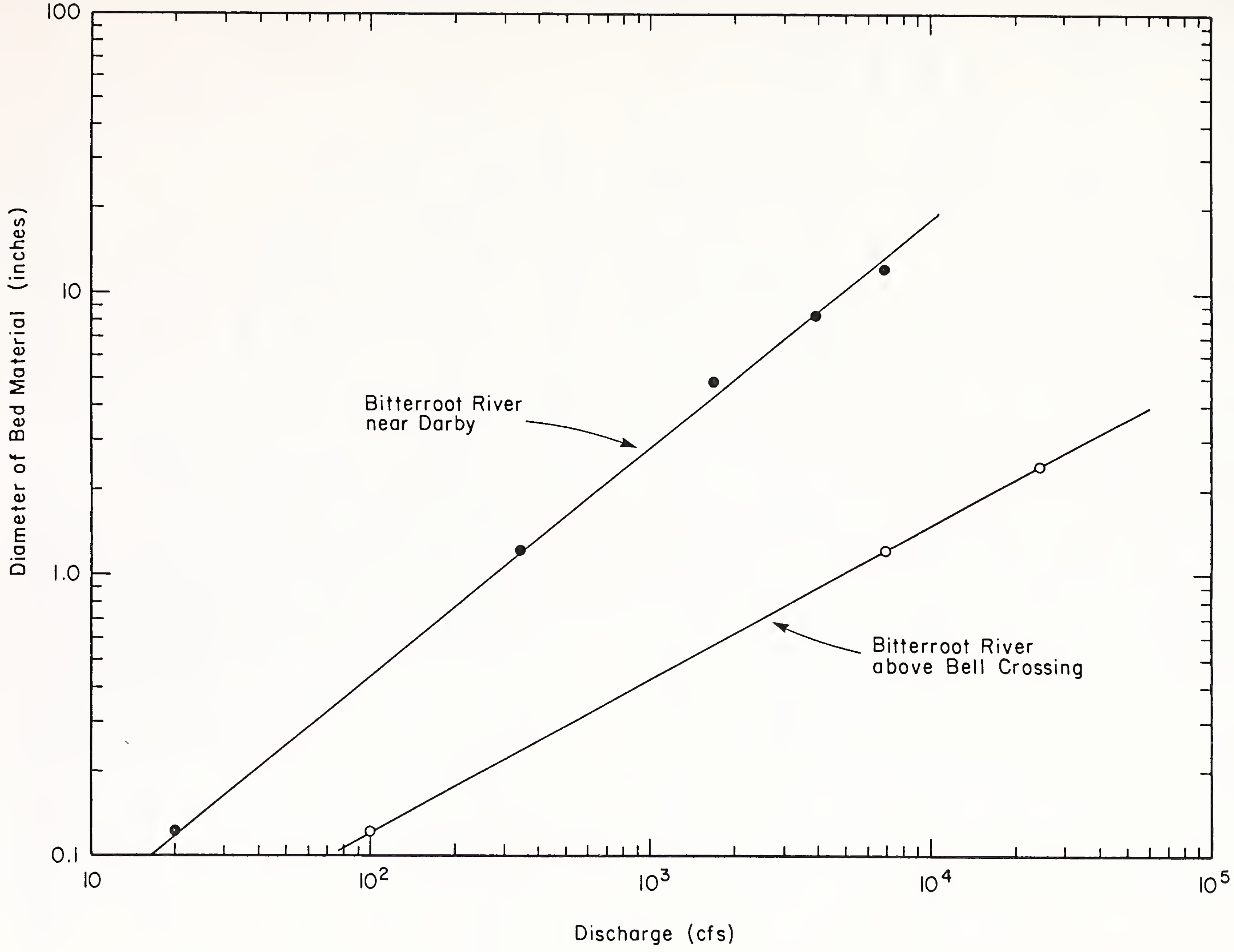


Figure 43. Size of Bed Material Moving at Different Flows: Bitterroot River.

44 and 45 illustrate the channel geometry at the Bell Crossing site (FEMA, 1980). The site was checked on a 1976 aerial photograph to confirm the location of the main channel. From this cross section hydraulic parameters were computed (Table 11) and graphed (Figures 46 and 47). The channel slope was determined from a profile of the reach (Figure 48). The relation between velocity and flow was then graphed (Figure 43). Using this graph, flow Q_c can be determined, corresponding to the velocity, V_c, occurring at critical shear stress (Table 10). Q_c represents the flow required to put bed material of diameter D into incipient motion. At the Bell Crossing site, a flow of 5,000 cfs is required to move material one inch in diameter, while at the Darby site, this particle size is set into incipient motion by a flow of only 280 cfs (Figure 43). This difference results from different channel geometries. A wide, shallow channel requires more flow than a narrower, deeper one to achieve the same velocity.

4.5.3 Frequency of Particle Movement

An annual hydrograph illustrates how often a particular flow is exceeded during the year. Since the flows required to put various particle sizes into incipient motion are known, the hydrograph can be used to show how often these different sizes will be in motion during an annual cycle. Hydrographs for an average year (1975) and a flood year (1974) are presented. Flow records exist for the Darby site; however, for the Bell Crossing site it was necessary to use flow records from the DNRC gaging site below Burnt Fork Creek near Stevensville (this station is located about 8 miles downstream from Bell Crossing). The frequency of particle movement is represented by the hydrograph area below a line marking a particular sediment size (Figures 49 through 52).

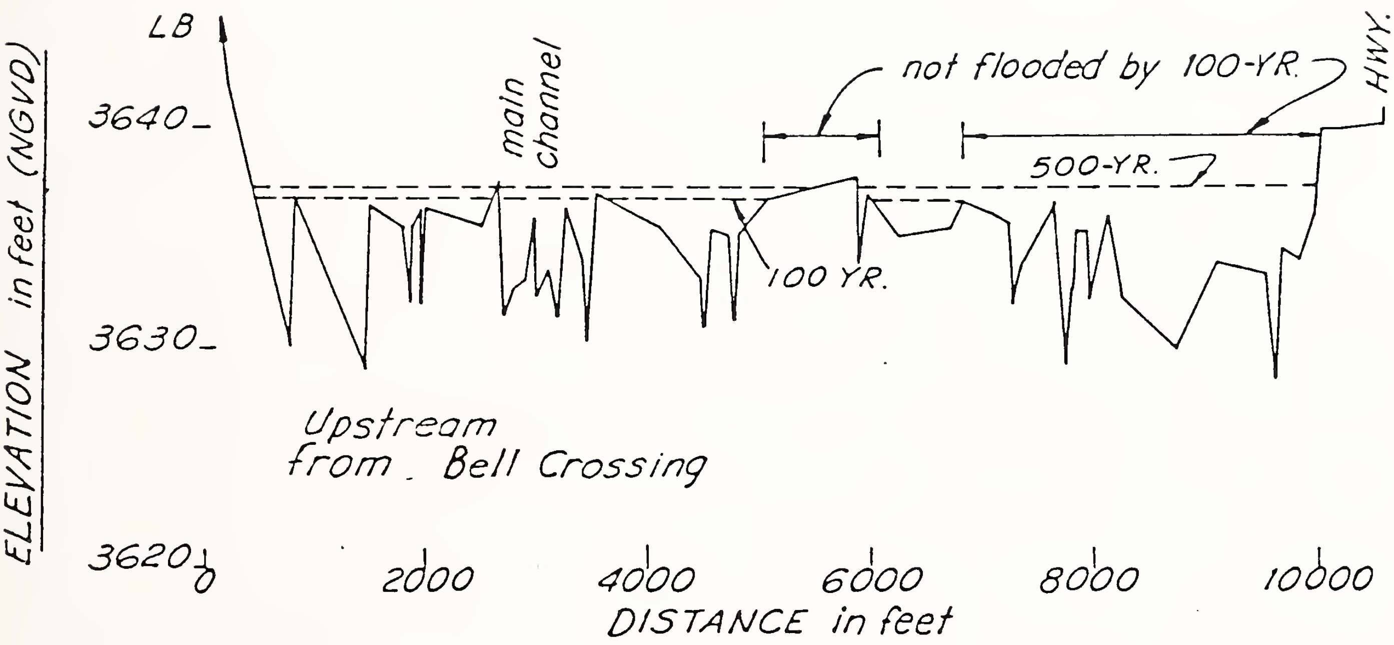


Figure 44. Bitterroot Valley Cross Section Above Bell Crossing (from FEMA, 1980).

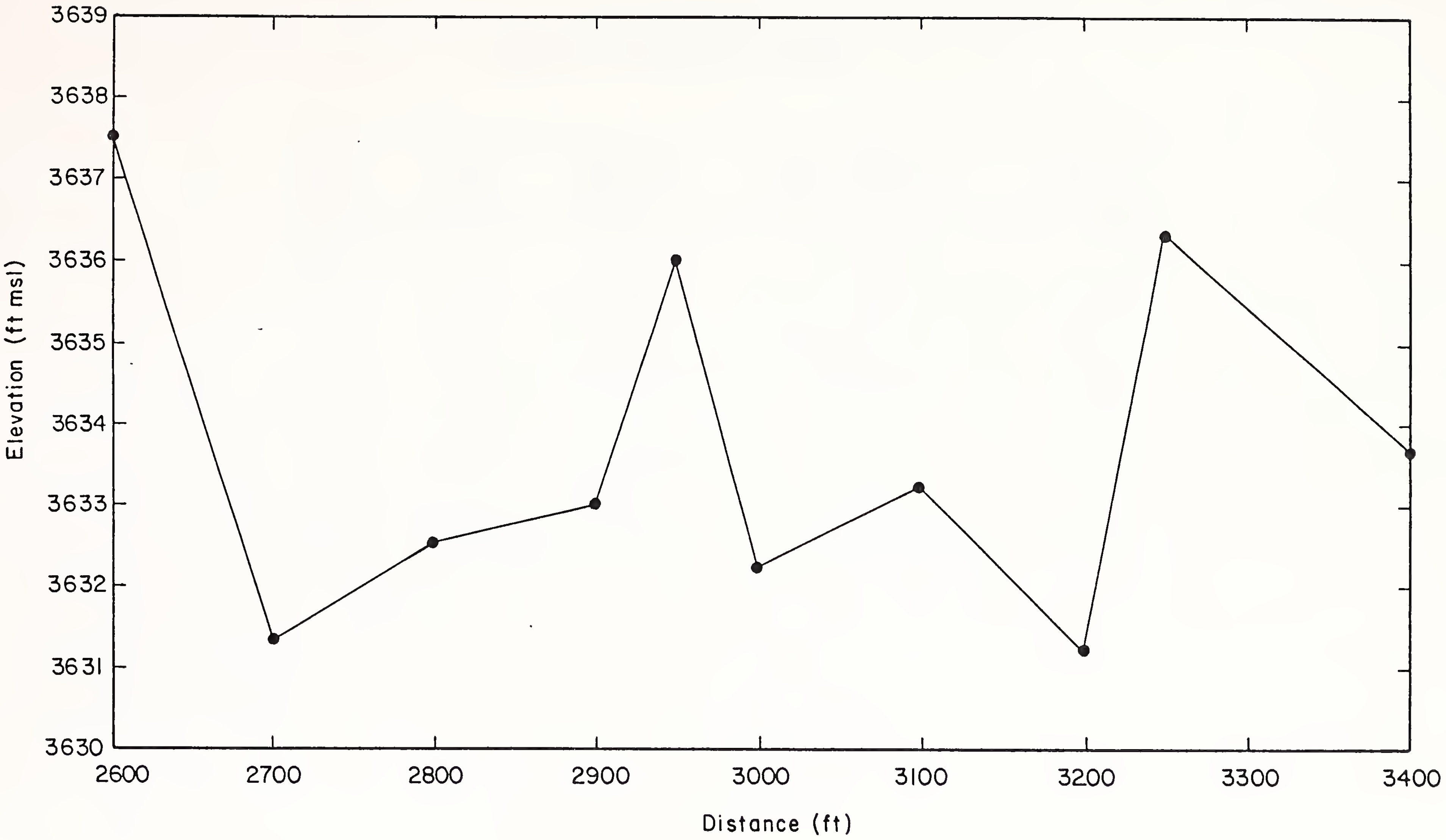


Figure 45. Cross Section: Bitterroot River Above Bell Crossing
Adapted From: FEMA, 1980.

Table 11. Hydraulic Parameters for Bitterroot River Channel Above Bell Crossing

Depth (ft)	Width (ft)	*Velocity (ft/sec)	Cross-Sectional Area (ft^2)	Flow (ft^3/sec)
0.5	87	1.48	18.5	27
1.0	175	2.35	88.2	207
2.0	475	3.74	437.5	1,636
3.0	529	4.90	953.5	4,672
4.0	587	5.93	1,532.7	9,089
5.0	633	6.89	2,141.7	14,756

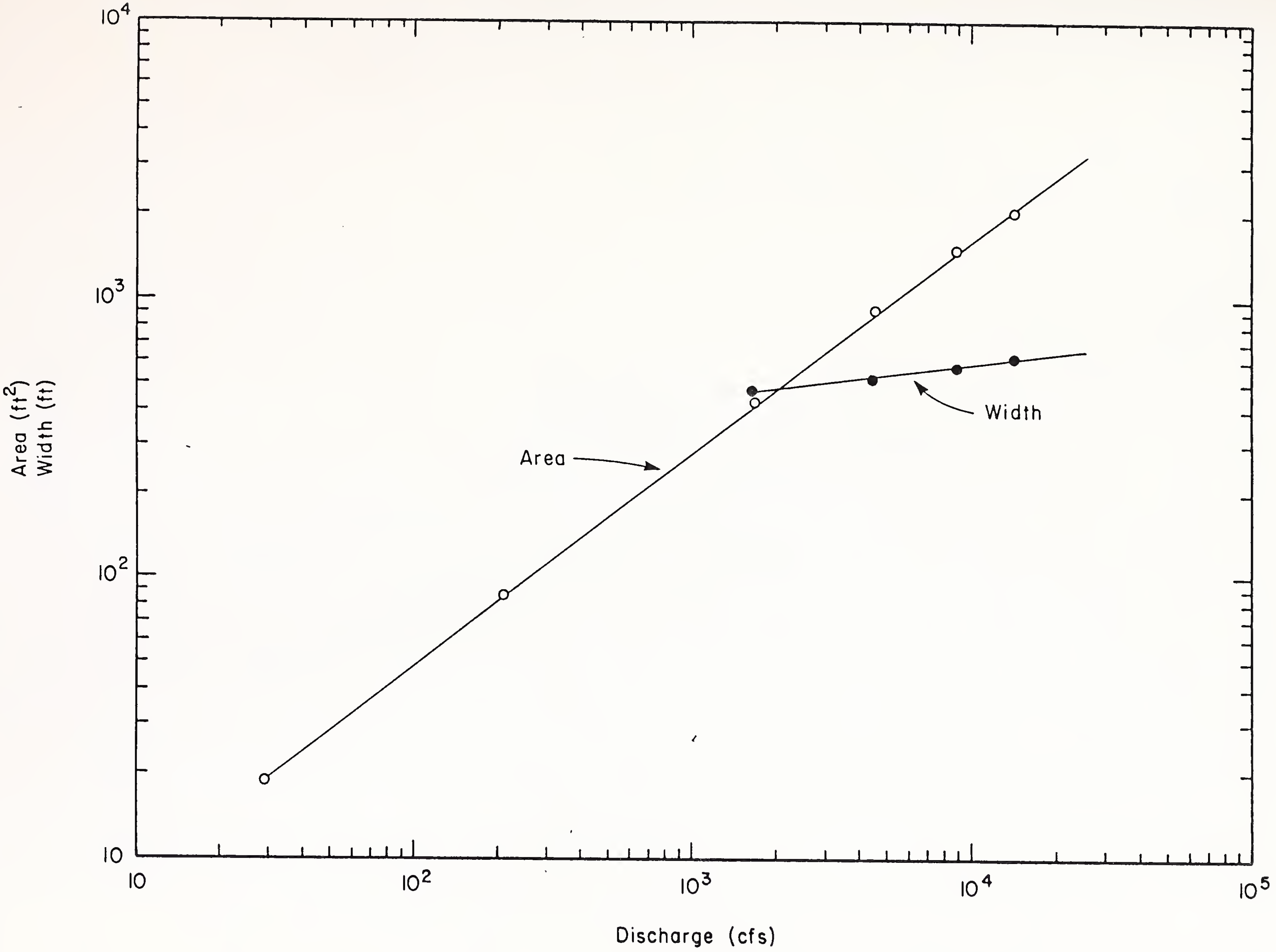


Figure 46. Channel Geometry: Bitterroot River Above Bell Crossing.

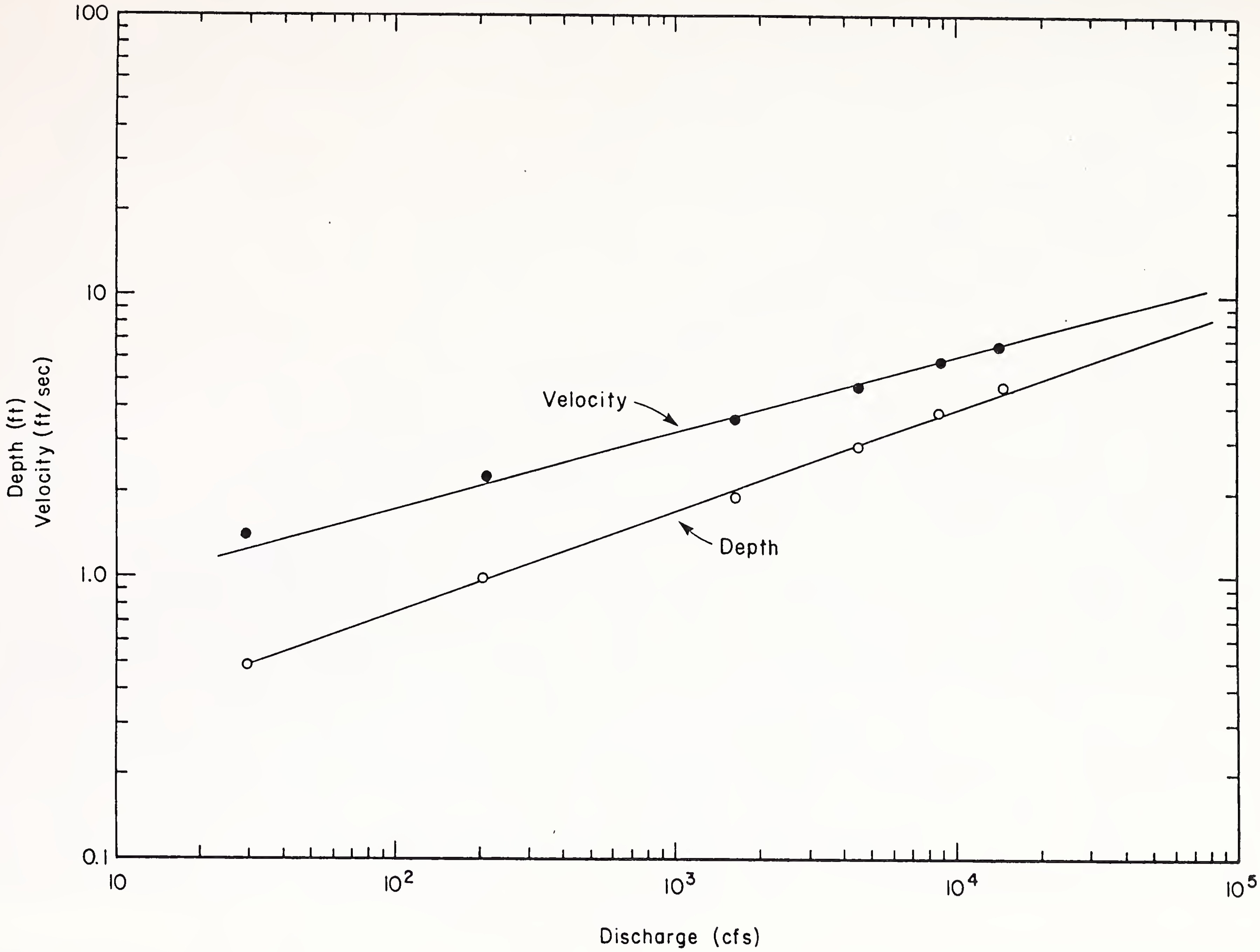


Figure 47. Hydraulic Parameters: Bitterroot River Above Bell Crossing.

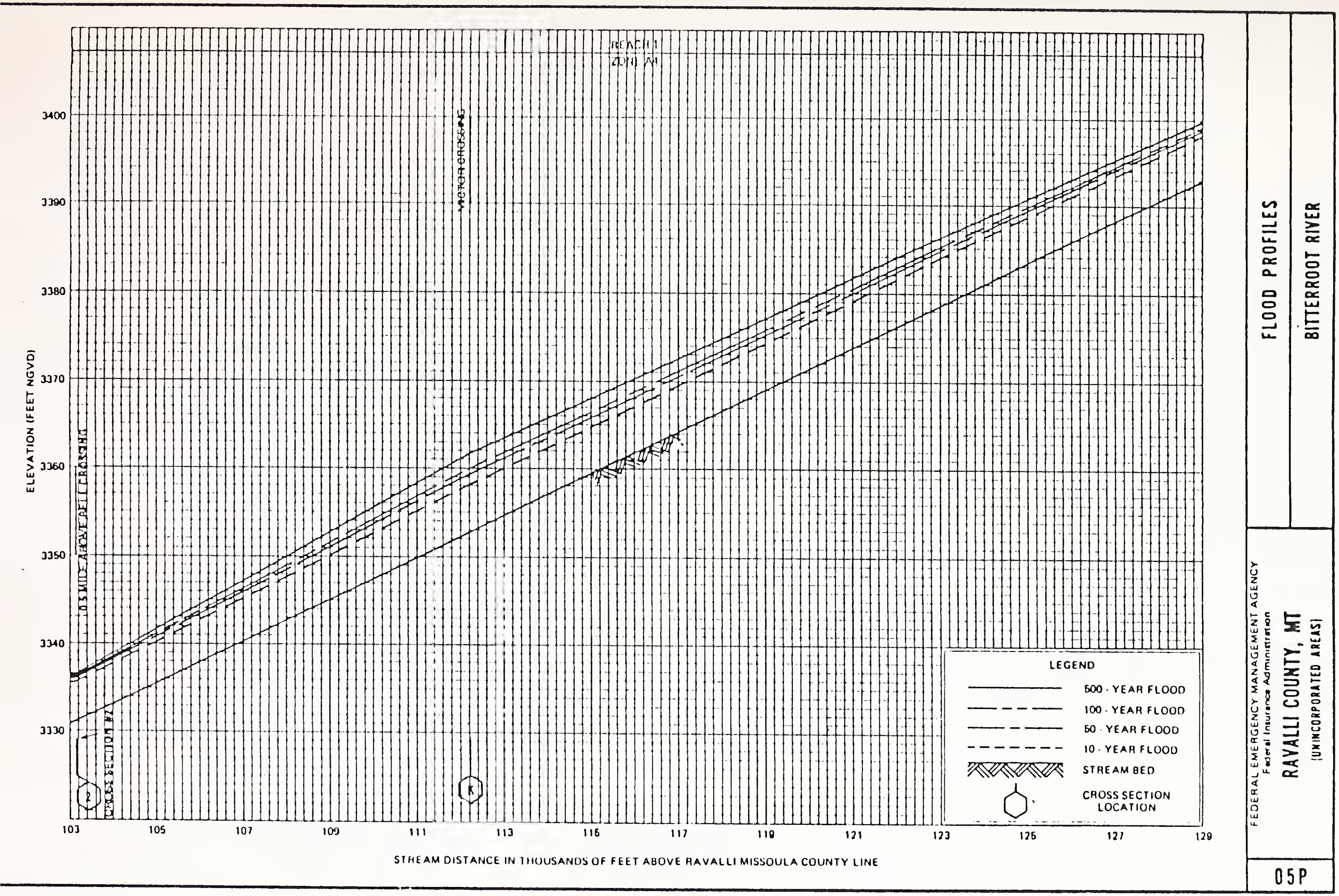


Figure 48. Bitterroot River Profile Near Bell Crossing (from FEMA, 1980).

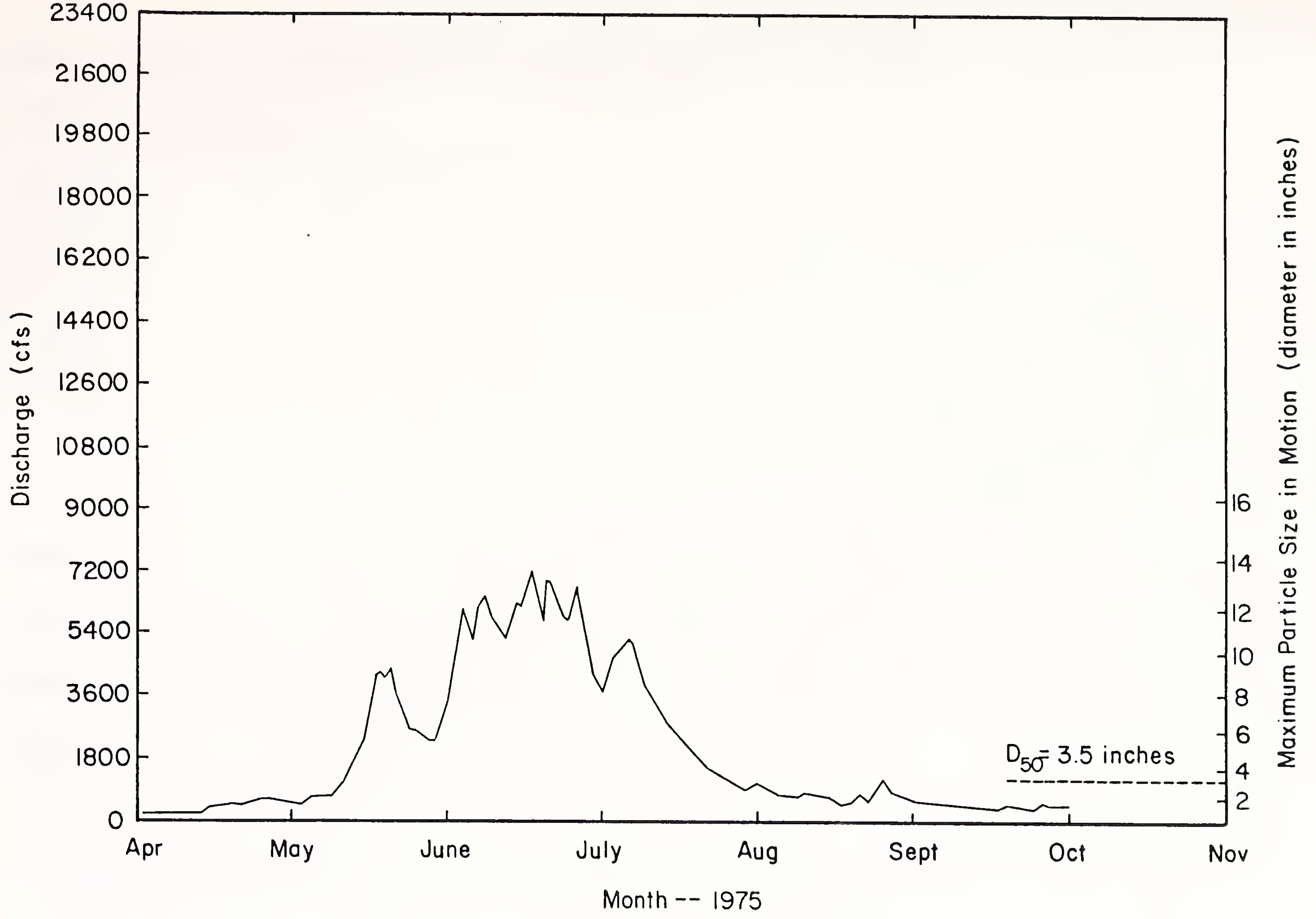


Figure 49. Frequency of Motion for Different Particle Sizes: Bitterroot River Near Darby 1975 (Average Year).

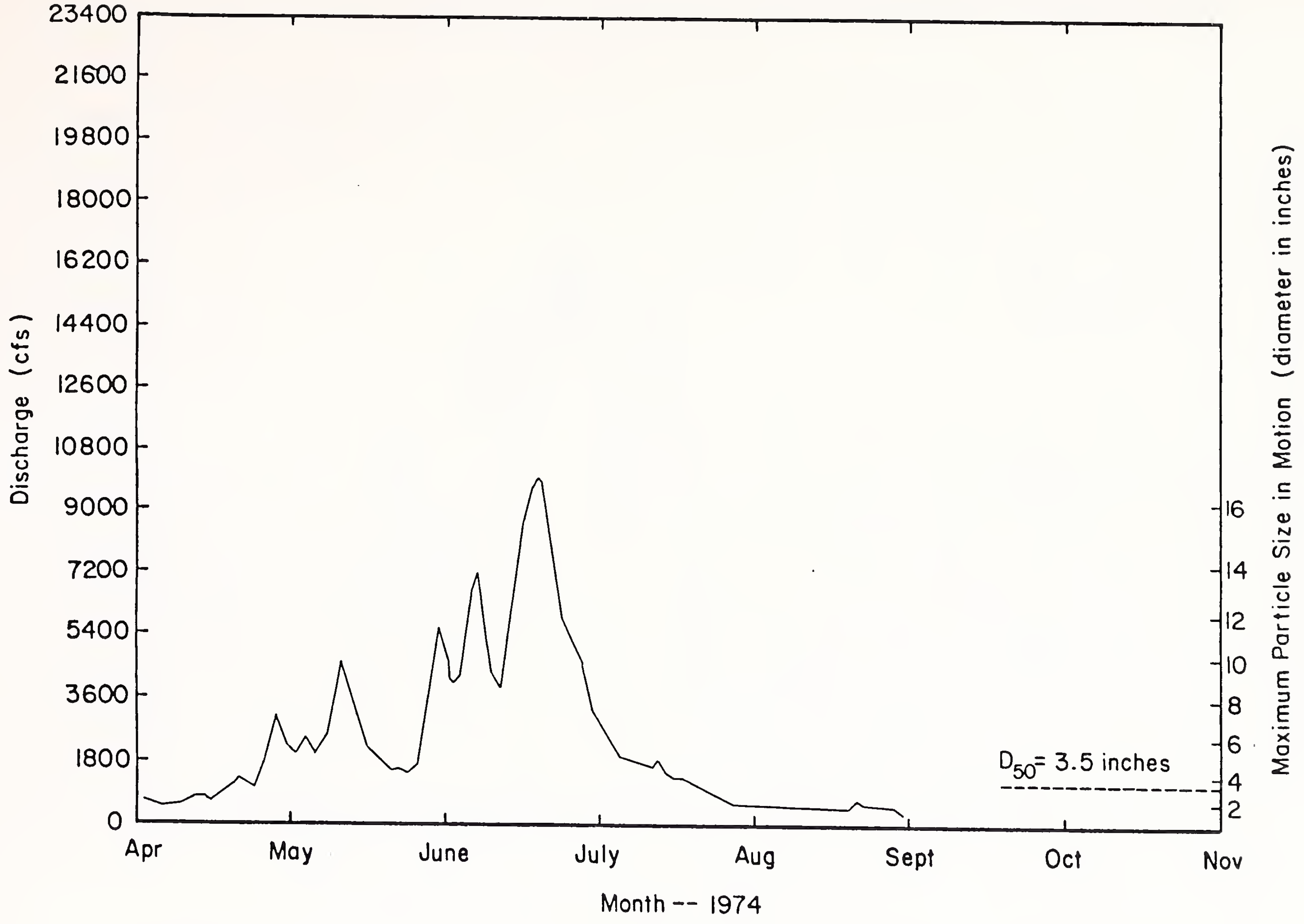


Figure 50. Frequency of Motion for Different Particles Sizes: Bitterroot River Near Darby 1974 Flood.

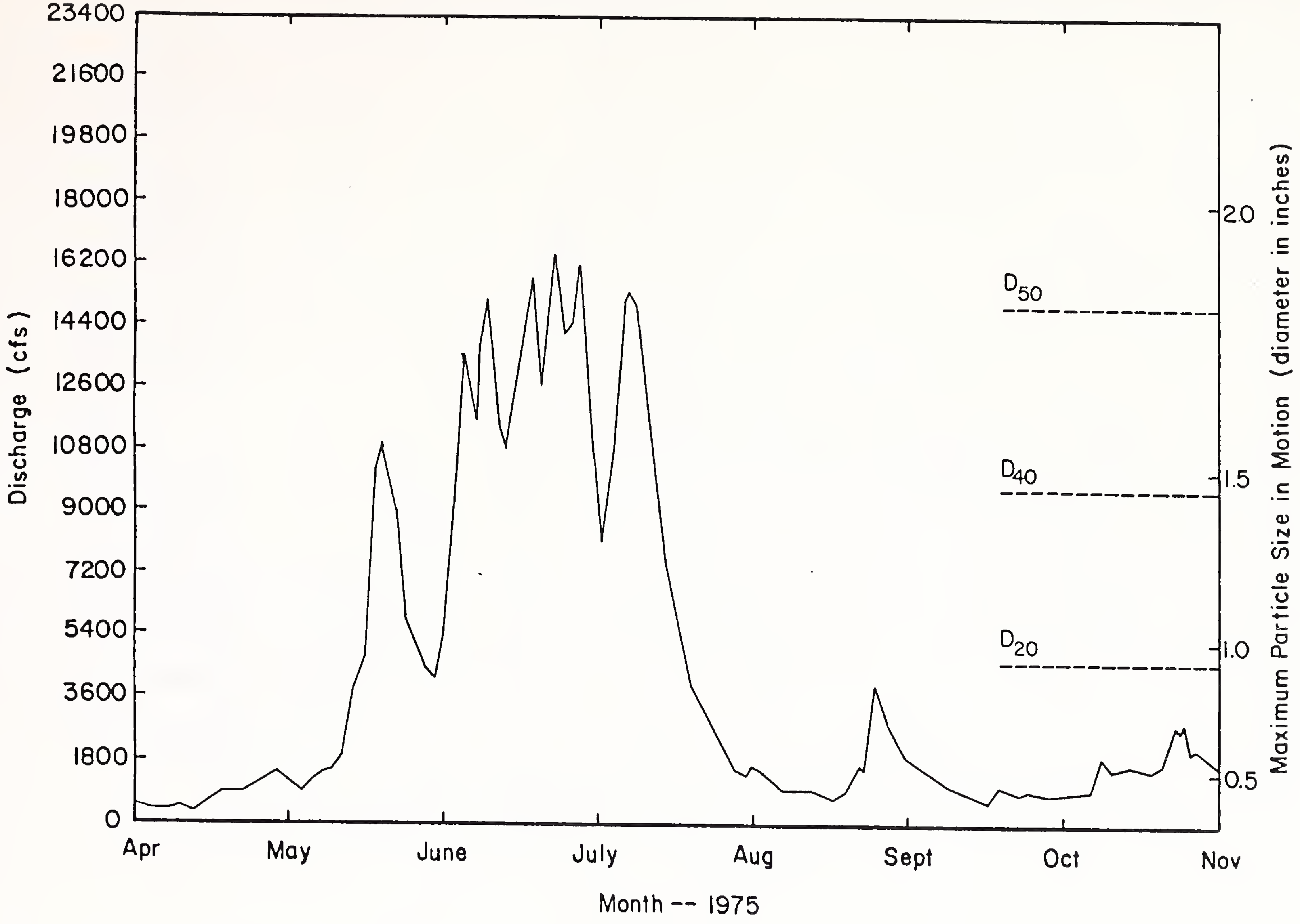


Figure 51. Frequency of Motion for Different Particle Sizes: Bitterroot River Above Bell Crossing 1975 (Average Year).

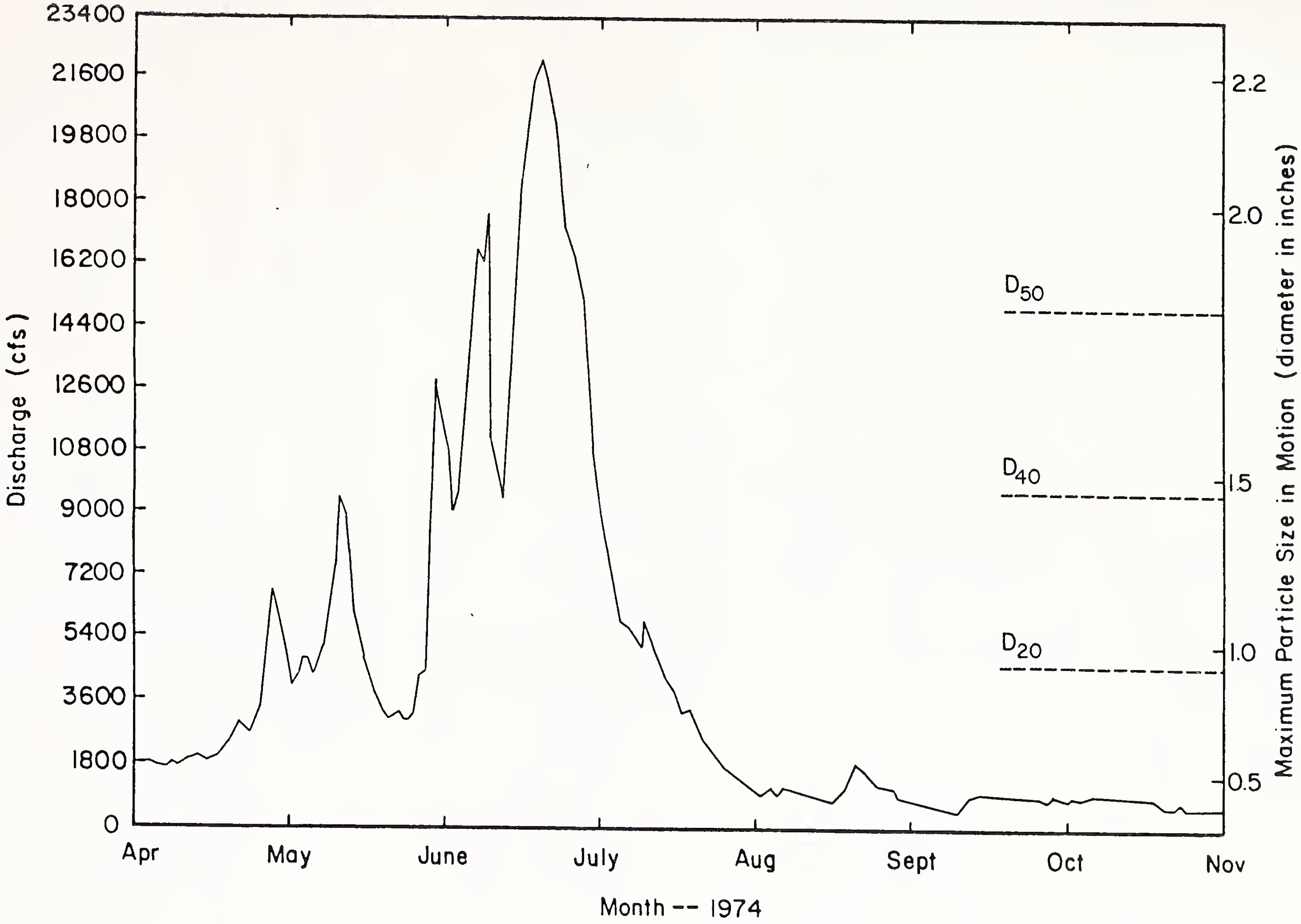


Figure 52. Frequency of Motion for Different Particle Sizes: Bitterroot River Above Bell Crossing 1974 Flood (50-Year Flood).

The sizes of materials composing the bed must be considered in conjunction with the frequency of movement of different sized particles. The median grain size (D_{50}) at Darby is about 3.5 inches, while at Bell Crossing the bed sediment is considerably smaller with a D_{50} of only 1.8 inches. The hydrographs at Darby indicate that from May through July the river is transporting particles larger than the median grain size (Figures 49 and 50). However, at the Bell Crossing site, particles larger than the median grain size are transported for only short intervals during June and early July. Inability to transport these sizes limits the tendency toward degradation. Comparing the 1974 hydrograph with that for 1975 it becomes apparent that more of these larger particles are transported during flood years (Figures 51 and 52).

4.5.4 Meyer-Peter, Muller (MPM) Bed Load Transport Equation

The following equation is assumed to describe bed load transport in the Bitterroot River at the Bell Crossing site (Meyer-Peter, Muller (MPM), 1948):

$$q_b = \beta_1(\tau - \tau_c)^{\beta_2}$$

where q_b = bed load discharge per unit width of channel

τ = boundary shear stress

τ_c = critical shear stress required to move a certain particle size

$\beta_1 = \dfrac{12.65}{\gamma_s \sqrt{\rho}}$

ρ = mass density of water = 1.94 lb sec^2/ft^4

γ_s = specific weight of dry sediment

β_2 = 1.5

This equation was used to compute bed load transport by size fraction for the 1-year, 10-year, 50-year, and 100-year floods. (A 1-year flood is a

magnitude of flow expected to be equaled or exceeded once per year). The size fraction approach is a more accurate method to computing total bed load discharge than calculation based on one representative size. The D_{20}, D_{40}, D_{60}, and D_{80} sediment sizes were determined using the size frequency distribution curve for river bed materials between Hamilton and Victor (Figure 34). The Shields relation was used to determine the critical shear stress, τ_c, for each of these sizes:

$$\tau_c = 0.047\ (\gamma_s - \gamma)D$$

where γ is the specific weight of water (62.4 lb/ft^3) and D is the particle diameter (ft). The shear stress, τ, that acts on the bed depends on the velocity, V, of the specific flow being considered:

$$\tau = \frac{f\rho}{8} V^2$$

where f is the Darcy-Weisbach friction factor (0.06 in this case). The relationship between flow and velocity at the Bell Crossing site was shown in Figure 47. Bed load per unit width was computed for each of the sediment sizes at a specific flow using the MPM equation (Table 12). For each flood flow, the four q_b values obtained for different particle sizes were averaged to determine $\overline{q}_b$ for each flow. This value must be multiplied by the top width of the river to compute total bed load transported. Figure 46 illustrated the relation between river width and water discharge.

The bed load moving during the 1-year flood is 1.5 ft^3/sec (10,718 tons/day). During the 100-year flood, the river transports 8.6 ft^3/sec (61,450 tons/day) as bed load (Table 13).

4.5.5 Suspended Sediment Transport: Colby Method

The Colby Method is commonly used to determine the volume of sand-sized particles capable of being transported by the river. Using this method

Table 12. Particle Sizes Composing Bed Load at Bell Crossing

	D		τ_c	Bed Load/Unit Width (ft^3sec)			
Particle	Diameter (mm)	Diameter (ft)	Critical Shear Stress (lb/ft^2)	$q_{b(1)}$ 1-yr flood	$q_{b(10)}$ 10-yr flood	$q_{b(50)}$ 50-yr flood	$q_{b(100)}$ 100-yr flood
D_{20}	24	0.08	0.39	$2.57 x 10^{-3}$	$1.31 x 10^{-2}$	$2.05 x 10^{-2}$	$2.34 x 10^{-2}$
D_{40}	37	0.12	0.58	0	$4.74 x 10^{-3}$	$1.03 x 10^{-2}$	$1.26 x 10^{-2}$
D_{60}	55	0.18	0.87	0	0	$4.07 x 10^{-4}$	$1.36 x 10^{-3}$
D_{80}	83	0.27	1.31	0	0	0	0

Table 13. Total Bed Load Moving During Various Flood Flows at Bell Crossing

Flood Return Period	Q Flow (cfs)	V Velocity (ft/sec)	τ Shear Stress (lb/ft^2)	q_b Bed Load Per Unit Width (ft^3/sec-ft)	W Width (ft)	q_b Total Bed Load (ft^3/sec)	(tons/day)
1-yr	8,000	6.0	0.520	2.57×10^{-3}	580	1.5	10,718
10-yr	17,300	7.3	0.775	8.94×10^{-3}	650	5.8	41,443
50-yr	22,800	7.9	0.908	1.04×10^{-2}	670	7.0	50,017
100-yr	25,500	8.1	0.955	1.25×10^{-2}	690	8.6	61,450

sediment discharge in the Bitterroot River above Bell Crossing was computed for the 1-year flood. The peak flows are expected to be at least 8,000 cfs every spring at this location. Using the Colby method, values for velocity, width, and depth for the desired flow condition (8,000 cfs) were taken from Figures 46 and 47 and are presented in Table 14. The Colby method involves using Figure 53 to obtain the discharge of sand per foot of river width. Using a median grain size of 0.6 mm (coarse sand), a velocity of 6 ft/sec corresponds to 90 tons/day/ft of width for a depth of 10 ft and to 70 tons/day/ft of width for a depth of 1 ft (Figure 53). However, to determine the volume transported for the desired depth of 3.8 ft, it is necessary to plot the two points determined from Figure 53 on semi-log paper. Interpolating, a depth of 3.8 ft will then correspond to a sediment discharge of 77 tons/day/ft of width (Figure 54).

4.5.6 Sediment Supply

Based on the previous calculations the Bitterroot River at Bell Crossing is capable of transporting at least 44,660 tons of sand and 10,718 tons of bed load (Table 14) during at least one day every year. The question is, how large is the supply coming in from the tributaries? Is the river capable of moving all these sediment contributions?

The annual sediment load delivered to the river by tributaries is estimated to be about 50 tons/mi^2 (personal communication with Mr. Bob Hammer, 1980). The drainage area above Bell Crossing is close to 2200 mi^2 (the actual drainage area above the DNRC gaging station at Stevensville). Thus, a total of approximately 110,000 tons of sediment are delivered to the river every year. Most of this sediment is the size of sand, or smaller. 44,660 tons of this sediment is moved during 1 day with a flow of 8,000 cfs (the flow with a 1-year recurrence interval). This leaves 63,340 tons of

Table 14. Colby Method of Determining Suspended Sediment Load: Bitterroot River Above Bell Crossing

Flow Recurrence Interval	Q_w Flow (cfs)	V Velocity (ft/sec)	d Depth (ft)	q_s Sediment Discharge (tons/day/ft of width)	W Width (ft)	Q_s Suspended Sediment (tons/day)
1-yr	8,000	6.0	3.8	77	580	44,660

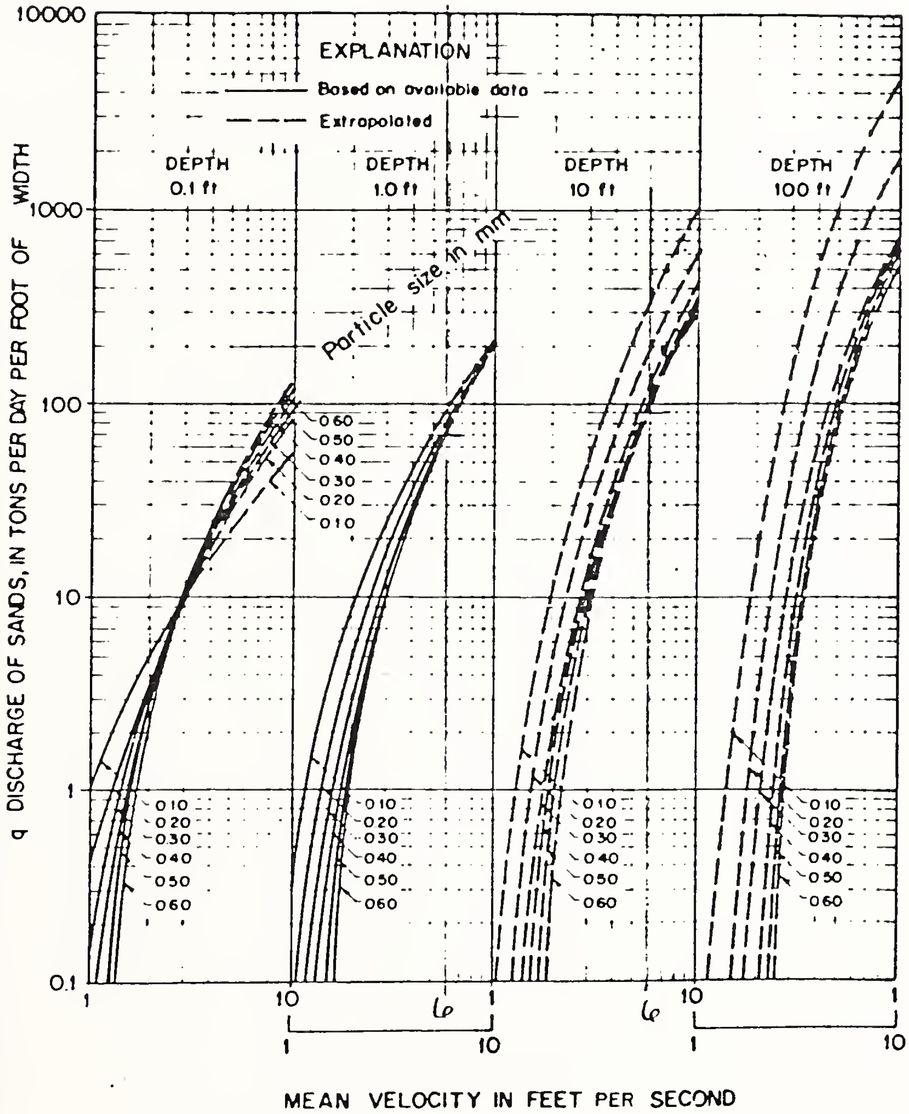


Figure 53. Relationship of discharge of sands to mean velocity for six median sizes of bed sands, four depths of flow, and a water temperature of 60°F (after Colby, 1964).

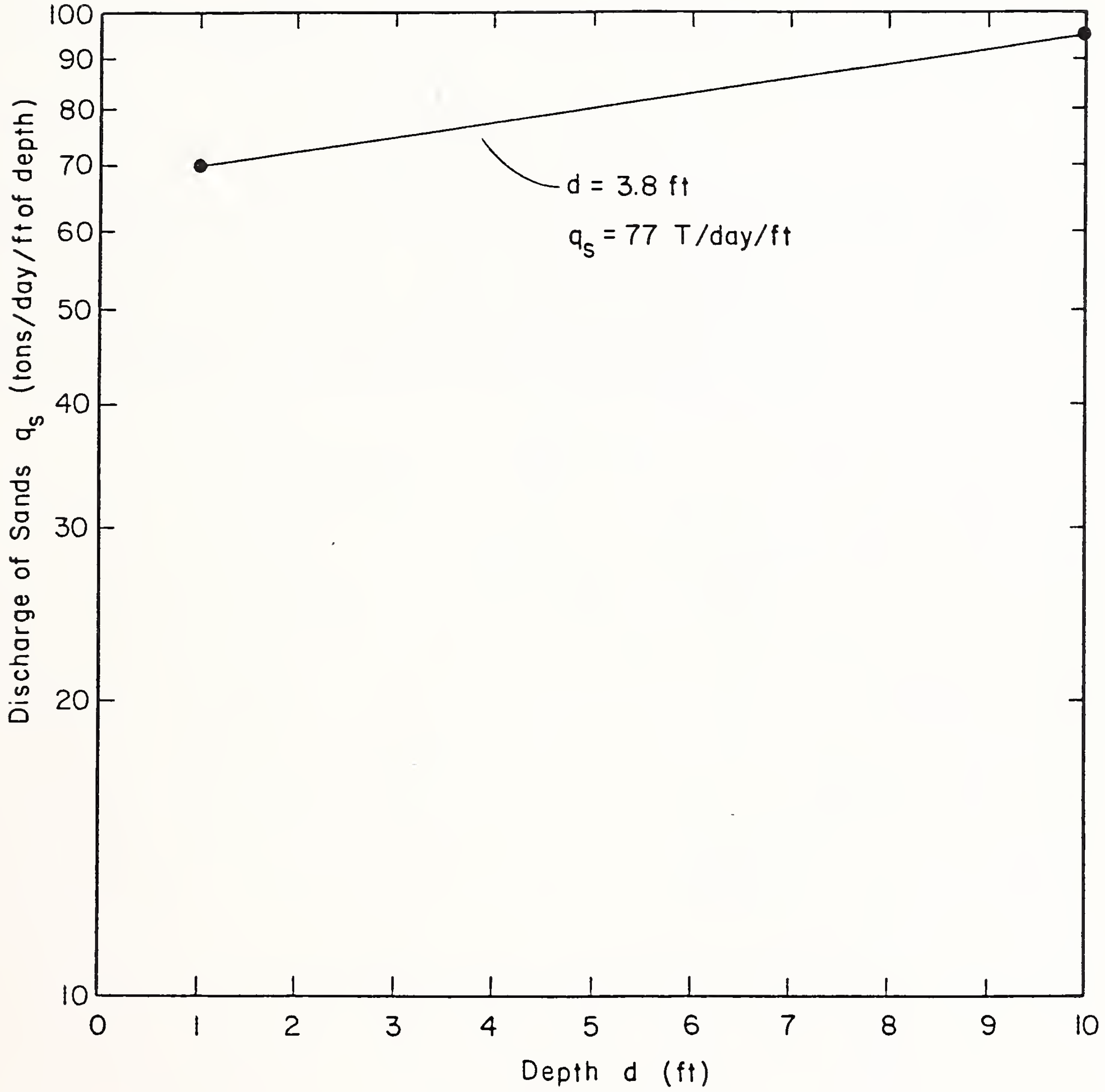


Figure 54. Determining Discharge of Sands for Depths Between 1 and 10 Feet.

sediment left to be moved the other 364 days of the year. Over a representative 10-year period, from 1968 through 1977, the average number of days during which the average daily flow exceeded 8,000 cfs was about 30 days per year (these values are based on the data from the DNRC gaging site below Burnt Fork Creek near Stevensville, a few miles below Bell Crossing)(Figure 55). Therefore, on the average 44,660 tons of suspended sediment are capable of being moved during 30 days of each year. This amounts to 1,340,000 tons of sediment annually, which is well above the 110,000 tons delivered to the river each year. Therefore, the suspended sediment load in the Bitterroot River is controlled by the supply from upstream watersheds.

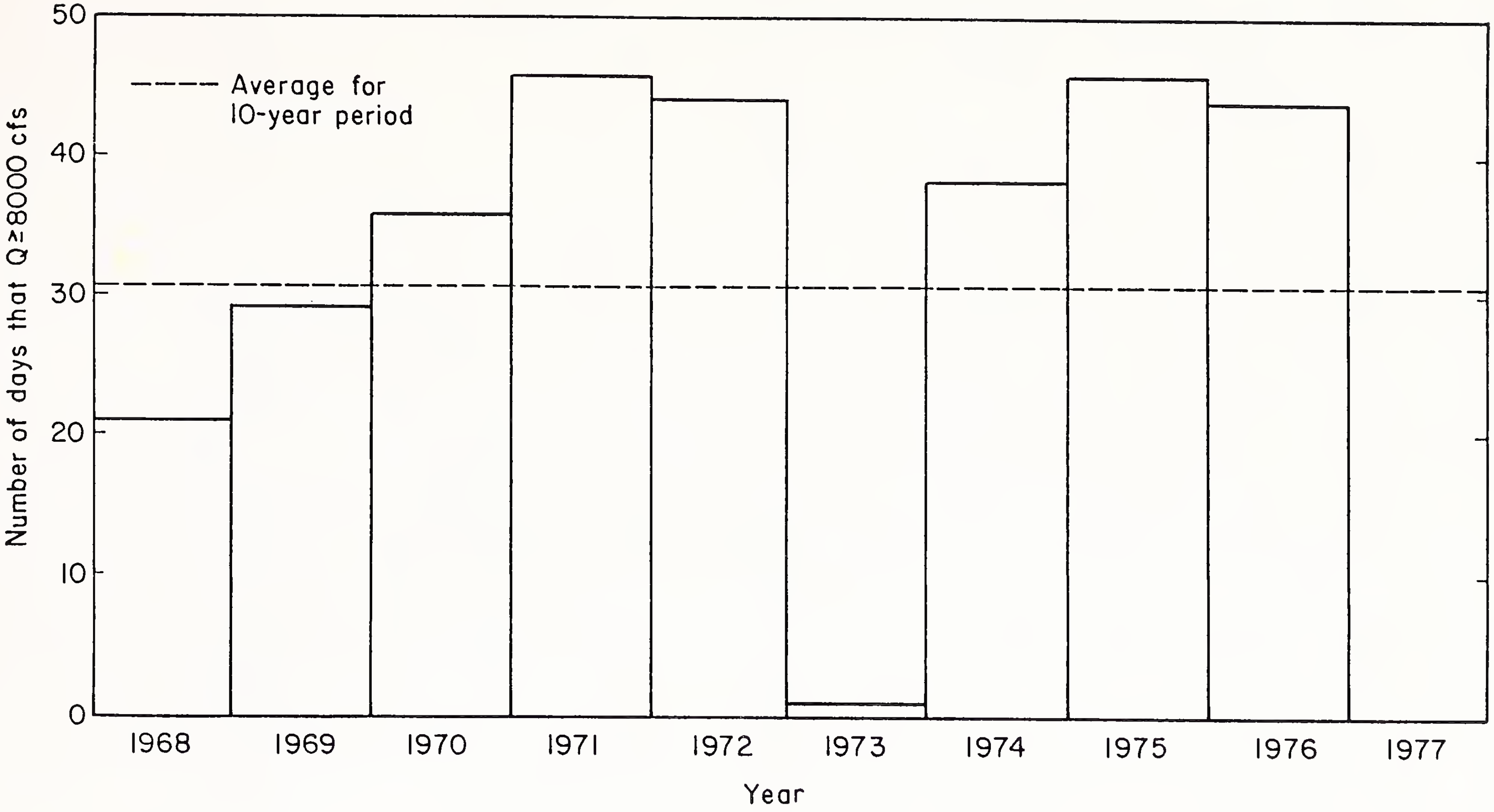


Figure 55. Number of Days Per Year That Flow Exceeded 8,000 cfs: Bitterroot River DNRC Station Near Stevensville.

V. AERIAL PHOTOGRAPH INTERPRETATION

Aerial photographs provide a historical record of changes in the river system. According to a quantitative analysis of 1936 and 1972 aerial photographs, the sinuosity of the Bitterroot River has decreased since 1936 (Figure 56) and braiding has increased (Figure 57) (Cartier, 1980). By comparing 1979 photographs to those taken in 1937, it is possible to trace the change in channel location, gaining some insight into how the channel has shifted in the past 43 years. The reach extending from the vicinity of Tucker Crossing to Stevensville Bridge has altered its course substantially in certain sections. In several locations gravel bars have shifted, old loops have been destroyed, and new paths created. In other portions of the river only minor changes have occurred, particularly in the west branch of the river south of Victor Crossing. However, the east branch has been distinctly altered (Figure 58). Braiding has increased noticeably in both the section between Victor Crossing and Bell Crossing and the section north of Bell Crossing (Figures 59 and 60).

The different ways a river may alter its channel are illustrated in Figure 61. Meander cutoffs commonly occur in two ways, either by neck cutoff or by chute cutoff. Cutoffs increase the bed slope, thereby contributing to river braiding. South of the Stevensville Bridge the river has cut off three bends, resulting in considerable straightening and steepening (Figure 62). Comparison of the 1937 and 1979 photographs clearly indicates the river channel is undergoing considerable readjustment. However, these changes appear to be a response to the natural characteristics of the hydrology and geology of the area.

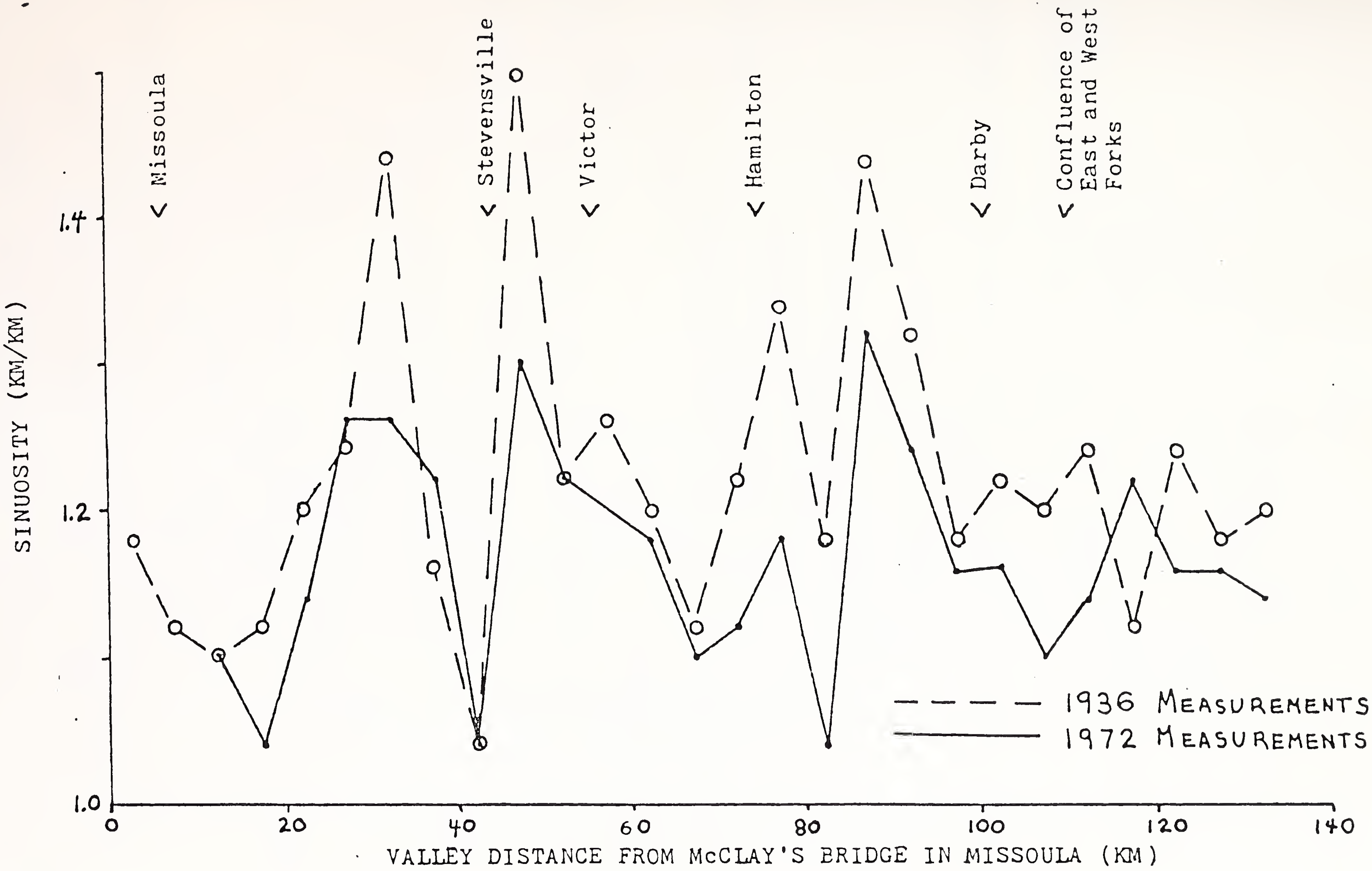


Figure 56. Sinuosity of the Bitterroot River (from Cartier, 1980). (Values taken at 5 km intervals.)

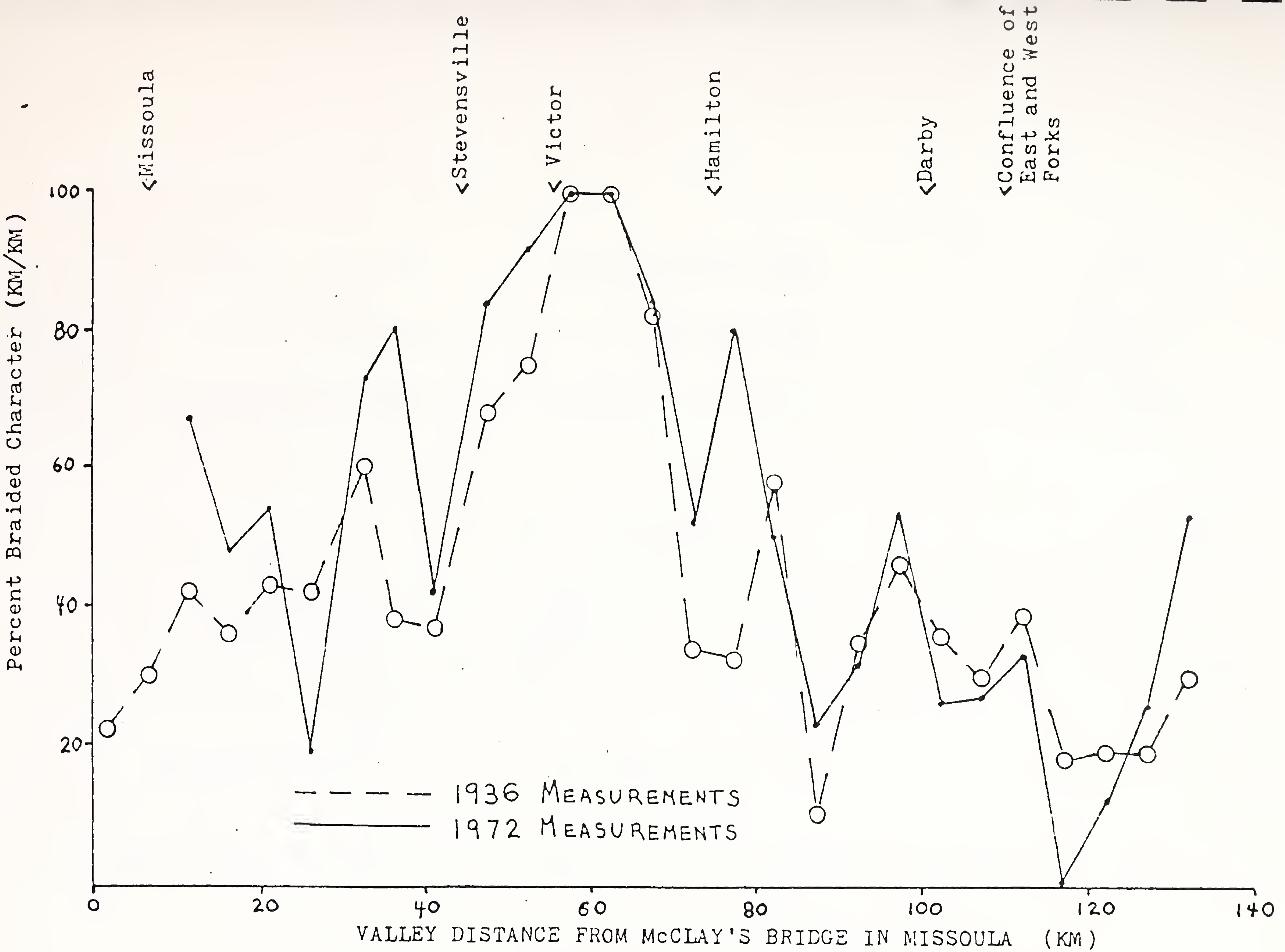
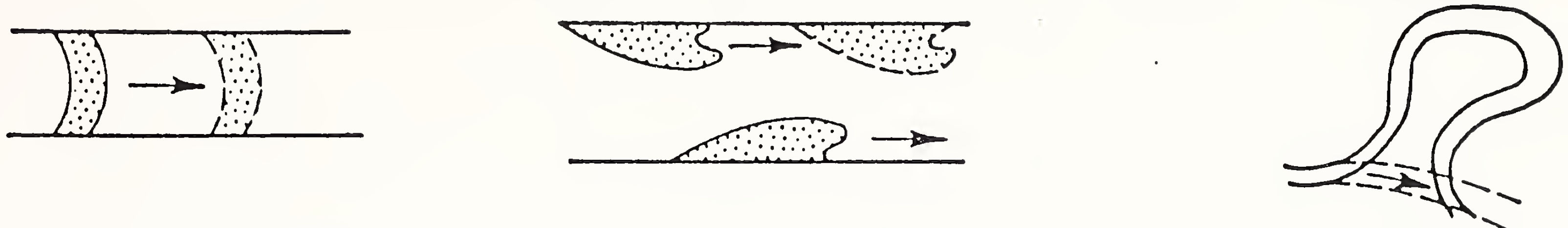
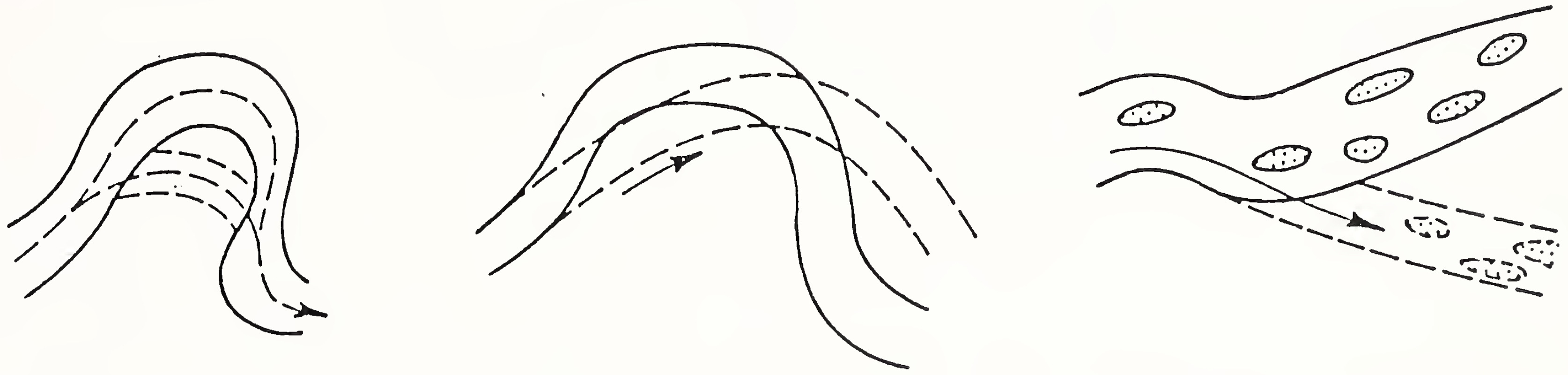


Figure 57. Braided Character of the Bitterroot River (from Cartier, 1980).
(Values taken at 5 km intervals.)



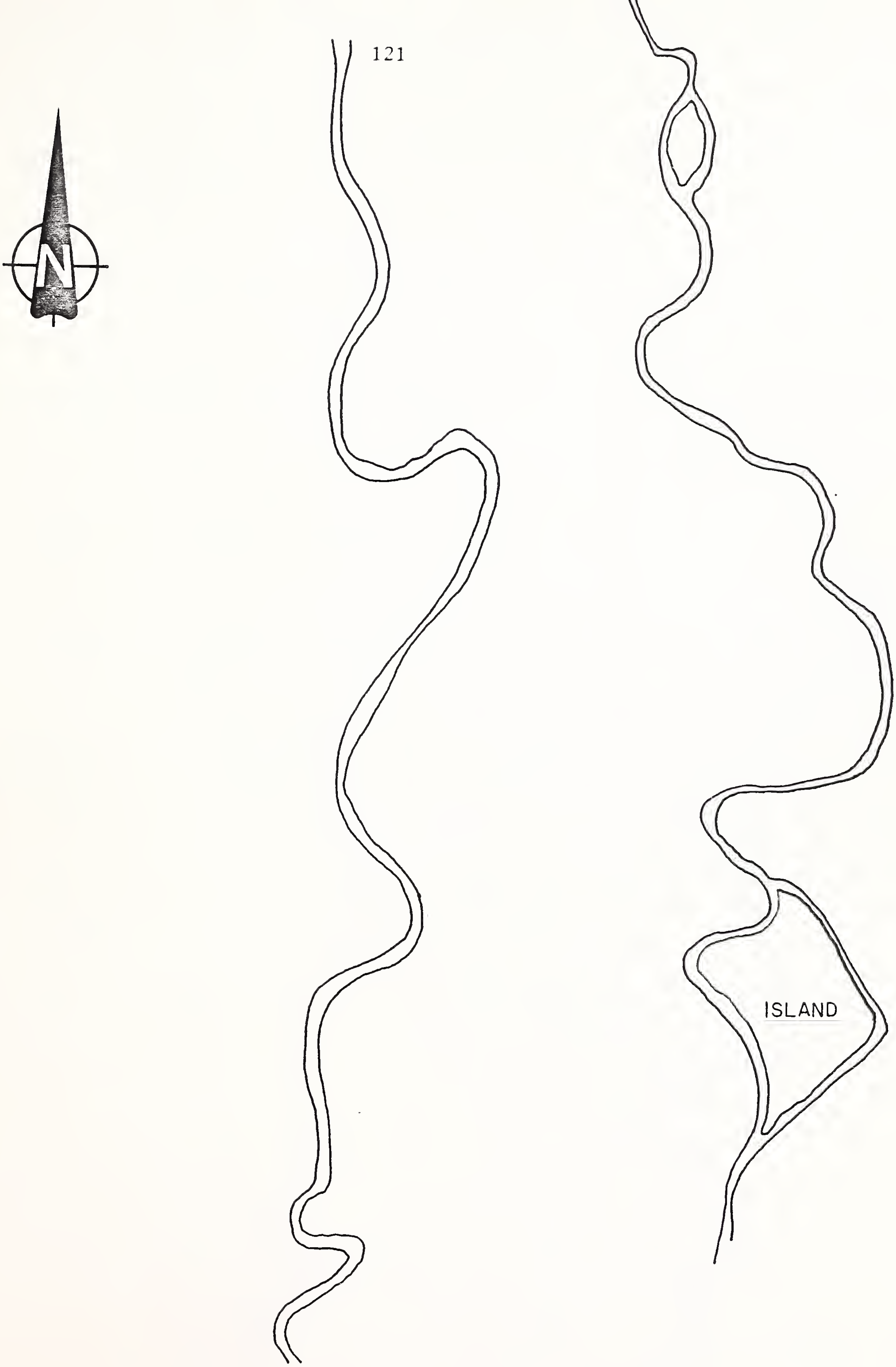
a. Transverse Bar Shift b. Alternate Bar Shift c. Neck Cutoff



d. Chute Cutoff e. Meander Shift f. Avulsion

(Solid lines indicate current status and dashed lines indicate future potential changes.)

Figure 58. Types of Channel Change (from Simons et al., 1980).



1979

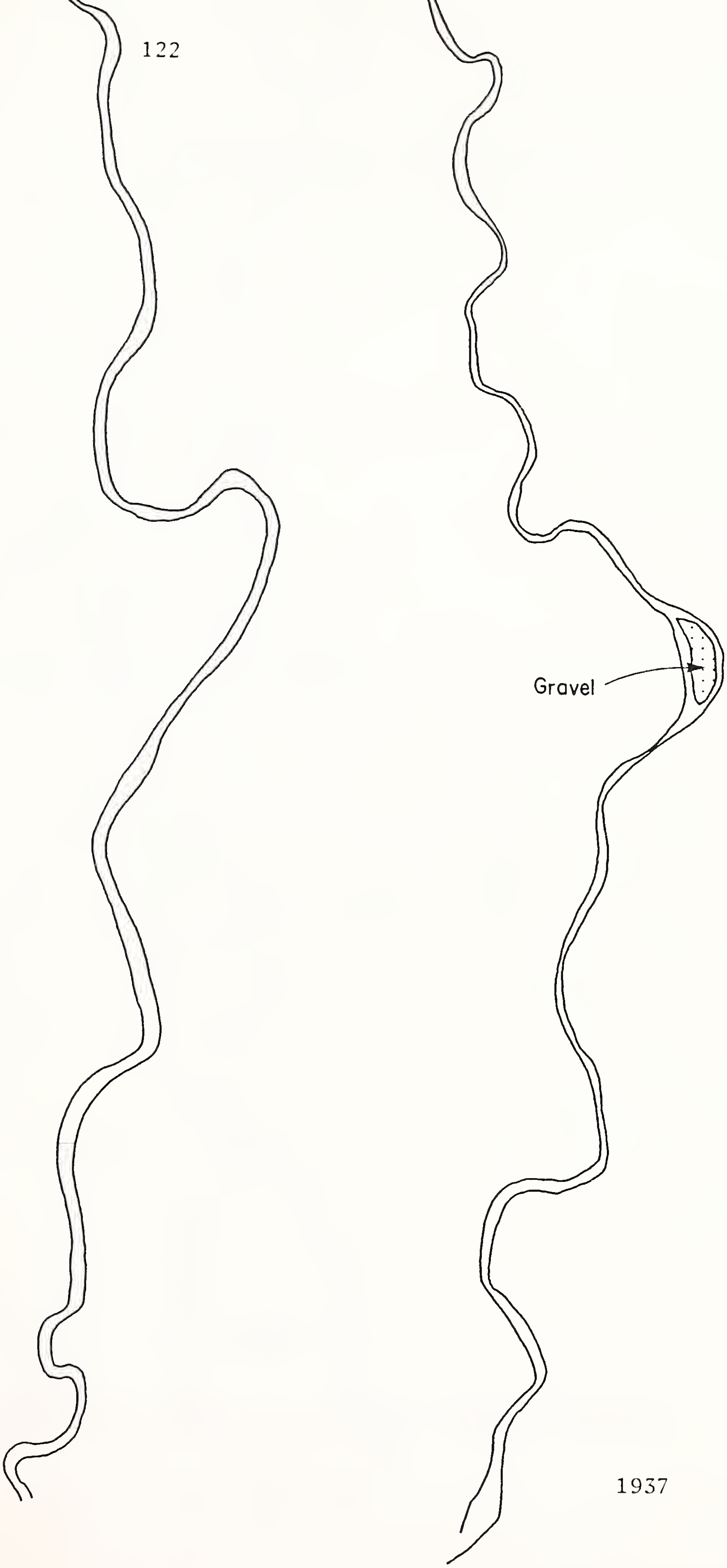
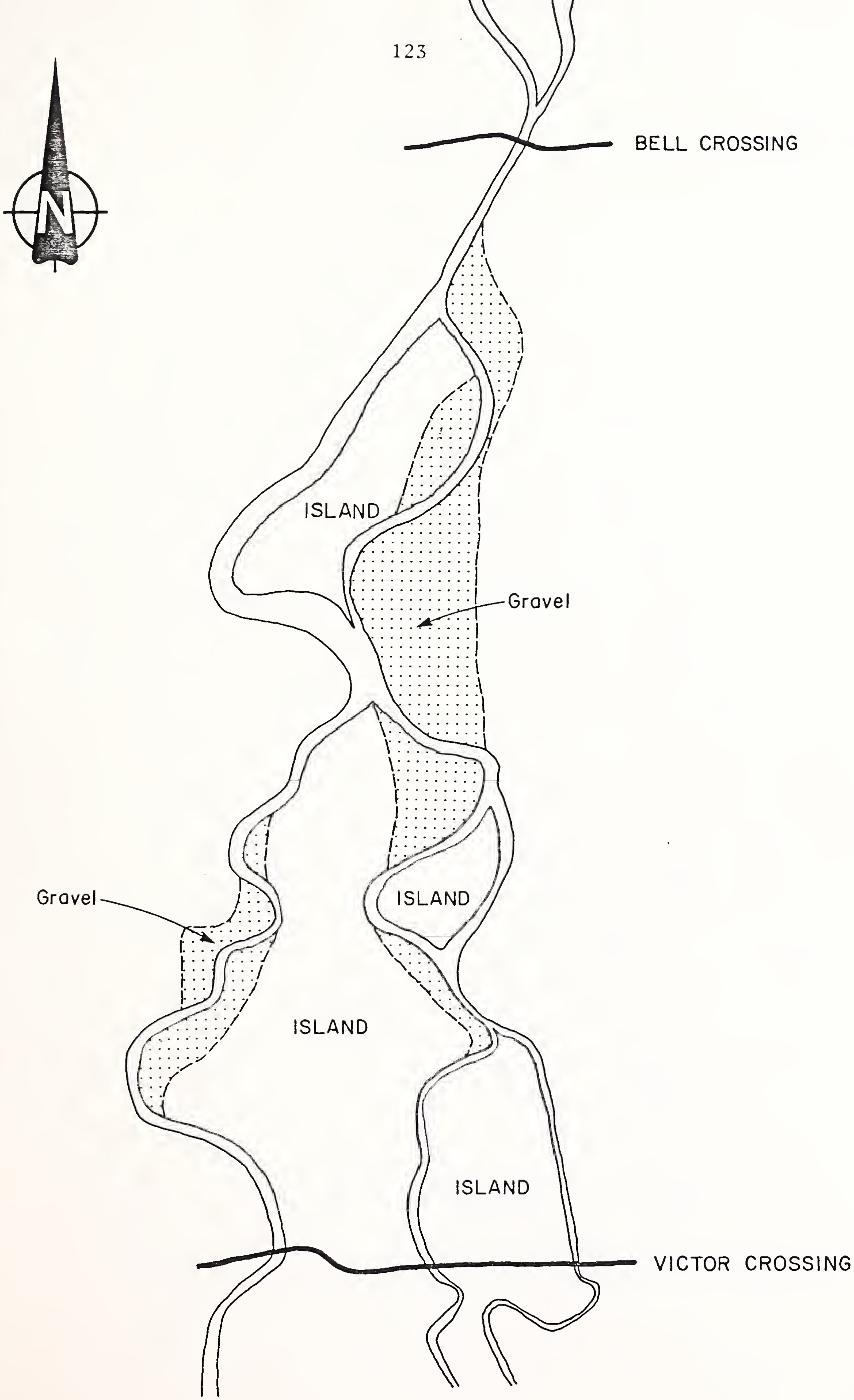


Figure 59. Bitterroot River South of Victor Bridge.



N
BELL CROSSING
ISLAND
Gravel
Gravel
ISLAND
ISLAND
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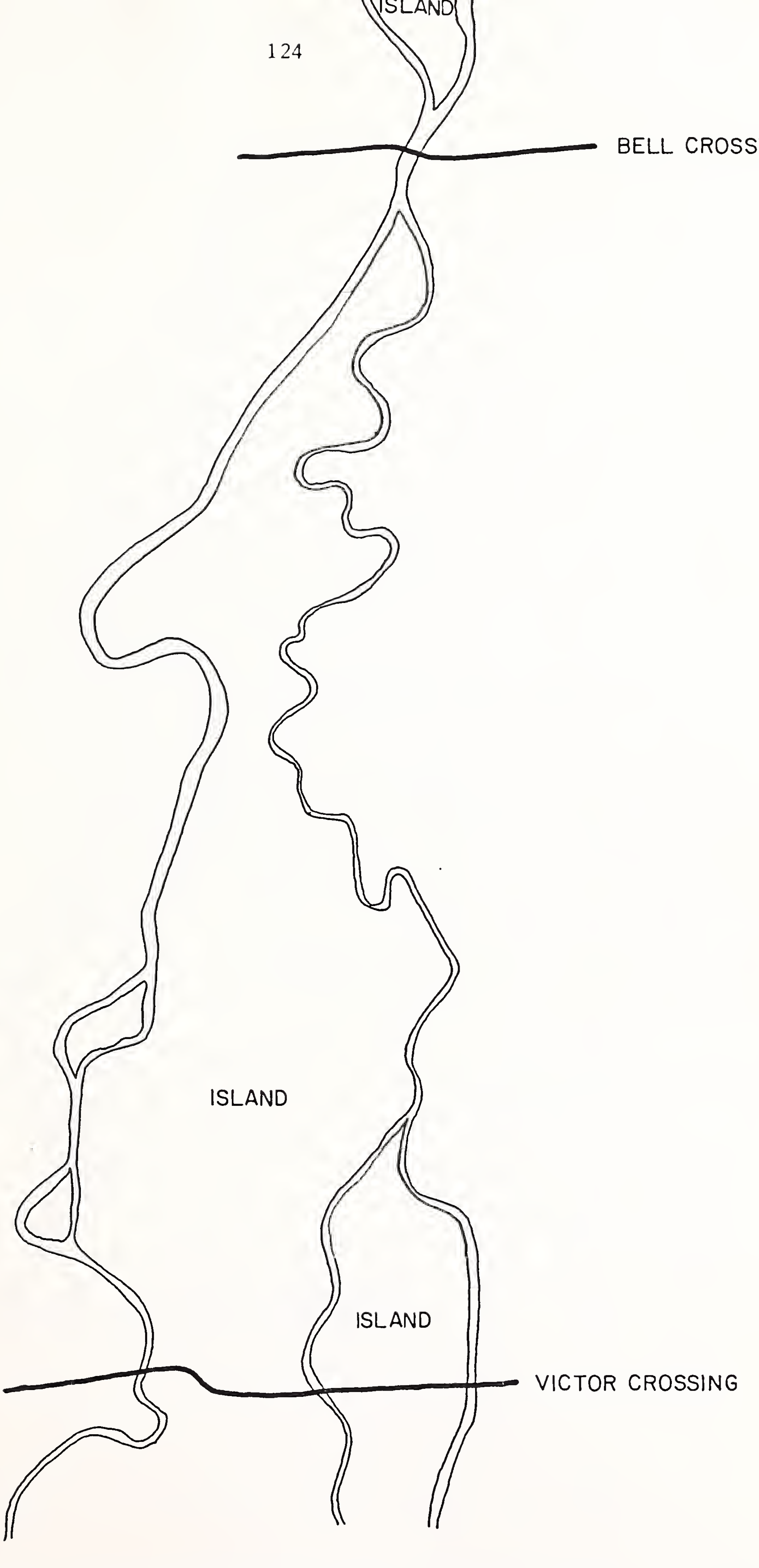
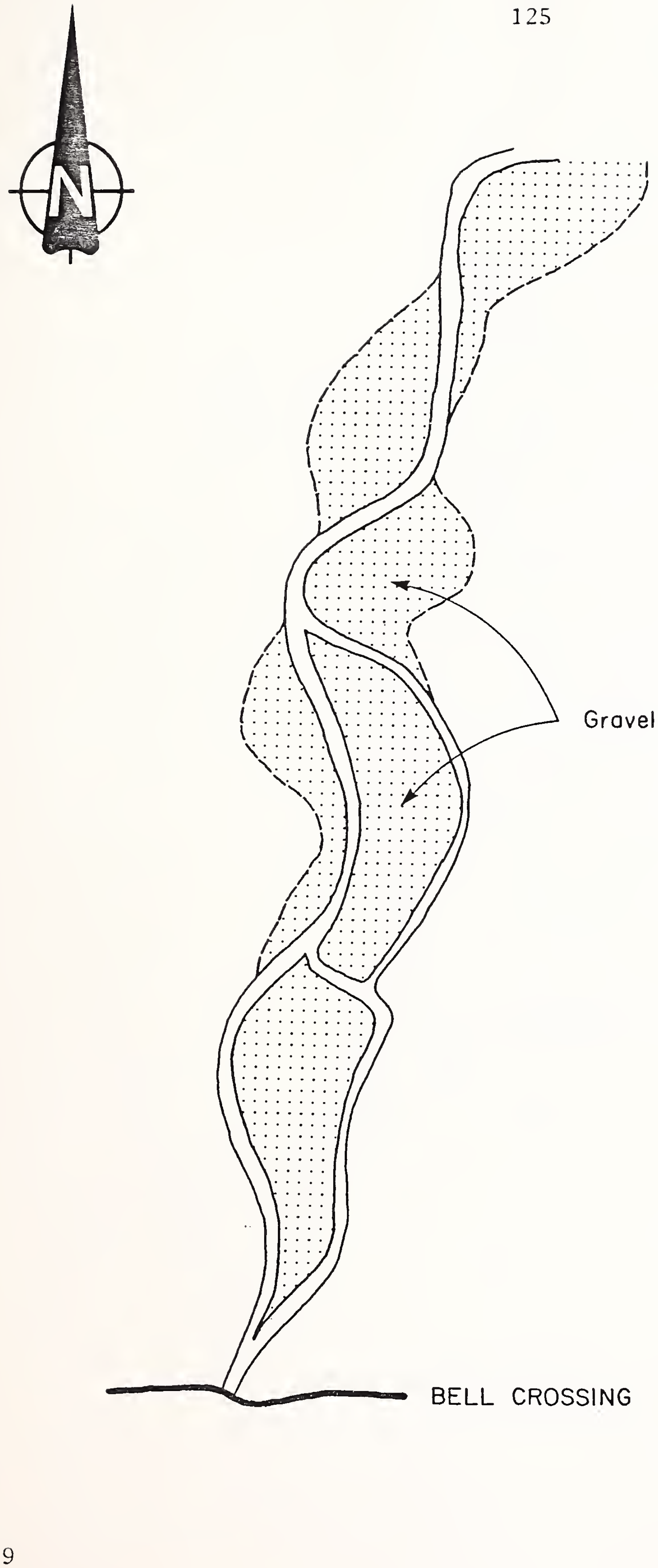
VICTOR CROSSING

1979

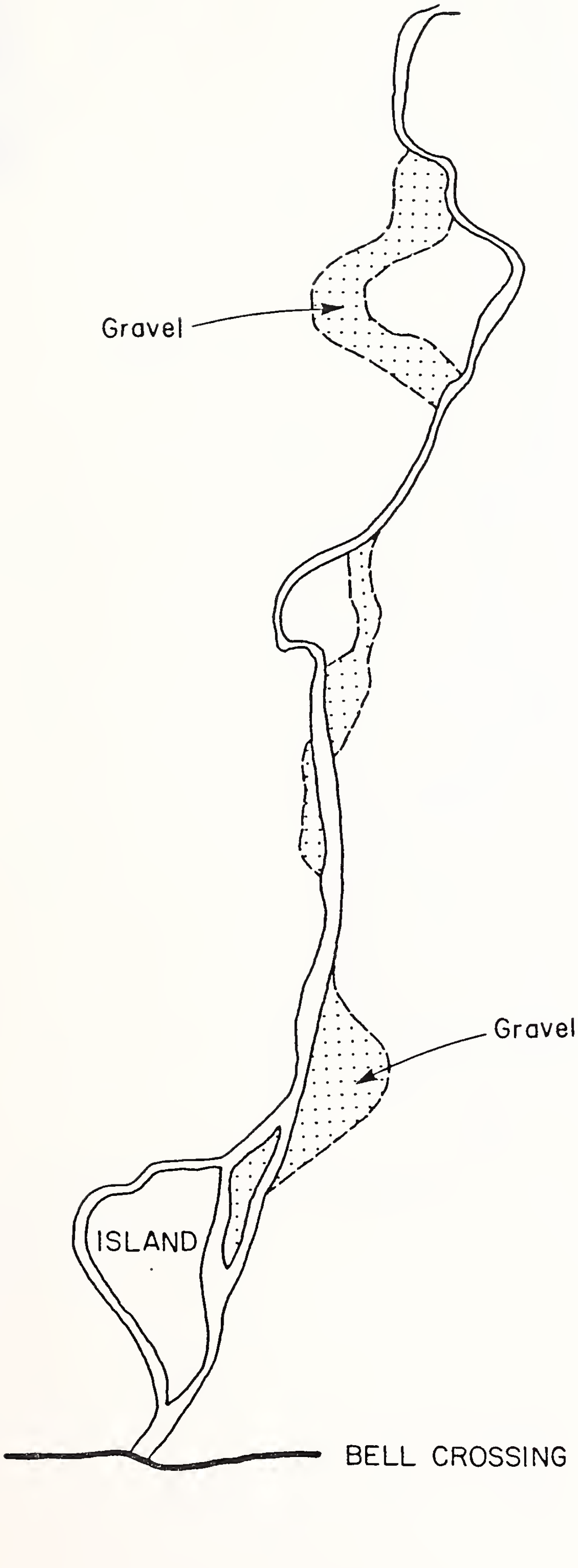


1937

Figure 60. Bitterroot River Between Victor Crossing and Bell Crossing.

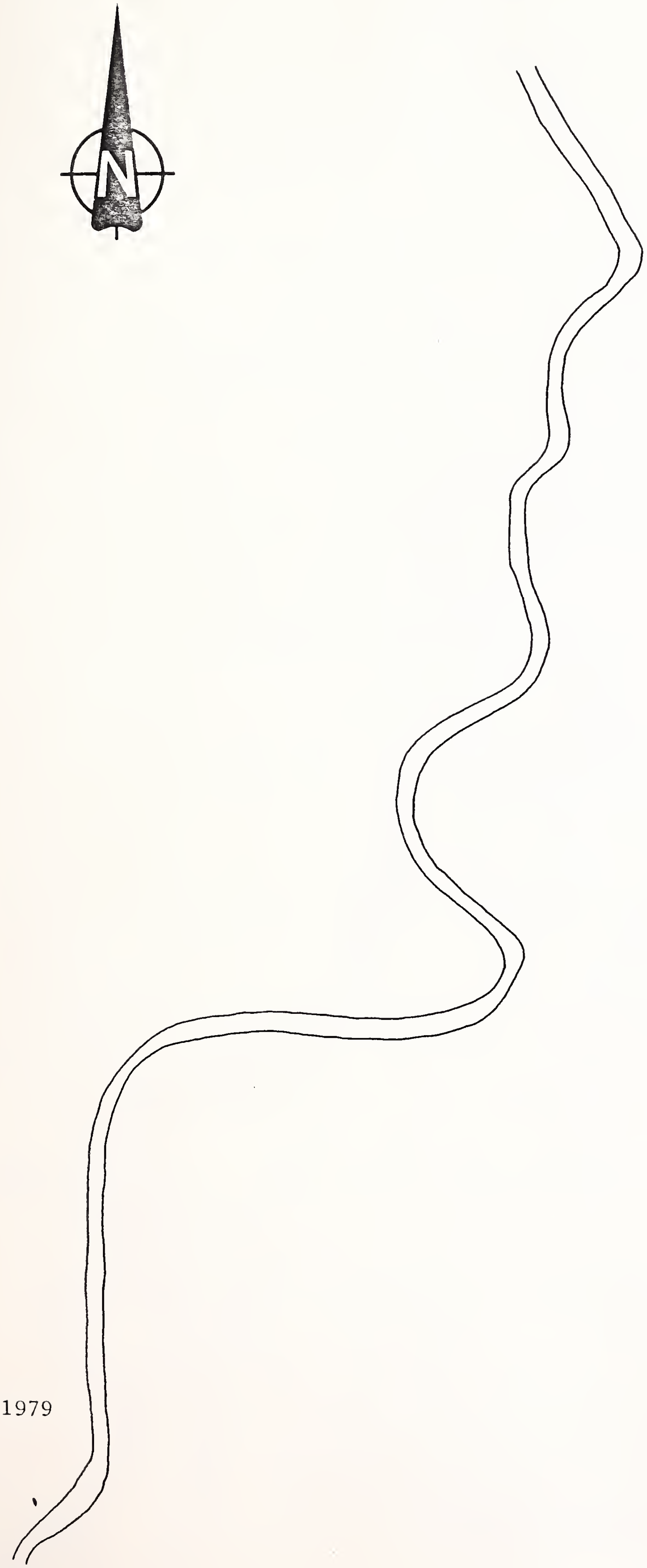


1979



1937

Figure 61. Bitterroot River North of Bell Crossing.



1979

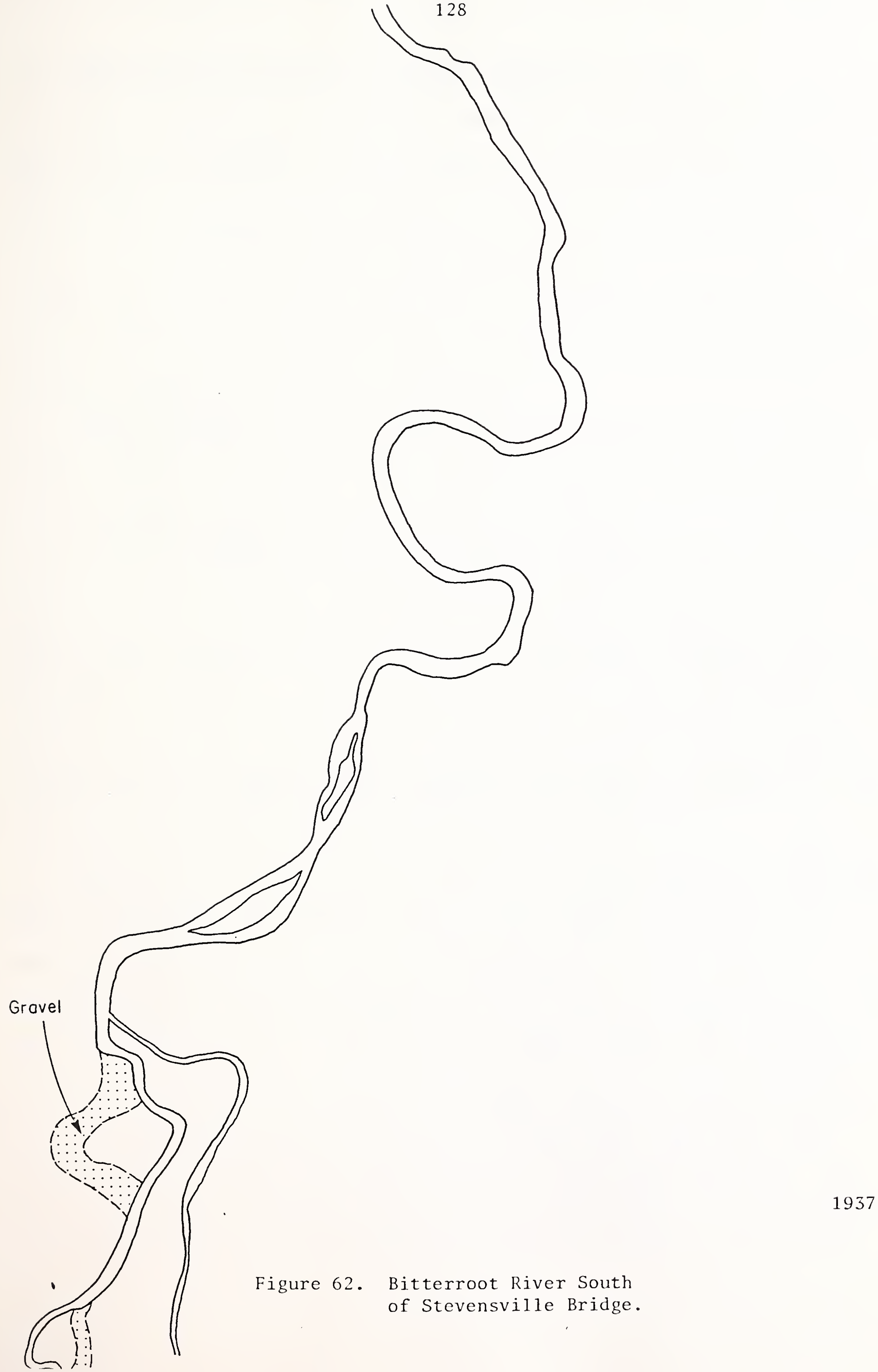


Figure 62. Bitterroot River South of Stevensville Bridge.

VI. CONCLUSIONS AND SOLUTIONS TO CHANNEL INSTABILITY PROBLEMS

Common characteristics of alluvial channels are the frequent changes in location, shape, and hydraulics that the channel and cross sections experience with time. These changes are particularly significant during periods when alluvial channels are subjected to high flows. Approximately 90 percent of all river changes occur during that five to ten percent of the time when major floods occur (if flow duration is significant). However, any modification of natural flows can significantly alter a river system.

Though the majority of changes will occur over comparatively short time periods, there can be regions within a river in which some degree of instability is exhibited for all flow conditions. Raw banks may persist on the outside of bends--the consequence of direct impingement of flowing water. Sloughing banks may occur due to seepage and other secondary forces created by water draining back through the banks to the river. Continuous wave action, generated either naturally or by man's activities, can also perpetuate erosion problems. Despite the numerous types of secondary bank erosion, the causes of bank erosion are normally small compared to the magnitude of erosion occurring during periods of high discharge and long duration.

Channel stability of the Bitterroot River has deteriorated during the past 40 to 50 years. The apparent cause of this change is the increase in annual peak flows since 1947. From 1937 through 1946, the peak annual flow averaged 4300 cfs at the Darby gaging site (Figure 11). From 1947 through 1978 this value increased to 7100 cfs, a 66 percent increase. For the Bitterroot River at Missoula, peak annual flow averaged 11,200 cfs from 1930 through 1946, and increased to 16,700 cfs from 1947 through 1978 (Figure 17). This change represents nearly a 50 percent increase in mean annual peak flow. The relatively low peak flows during the 17-year period from 1930 to 1946 created

a stabilizing effect on the Bitterroot River and allowed the formation and maintenance of meandering bends. The floods of 1947 and 1948 negated this condition, re-establishing the river in its braided condition. Since the river exhibits characteristics falling between the braided and intermediate river classification (Figure 52), it can shift between these two classifications depending on cycles in flow patterns, that is dry to wet and vice-versa. Drought years coincide fairly well with years of low peak flows. 1930-1940 and 1944-1946 were exceptionally dry years based on total annual precipitation records. Quite probably drought was responsible for the greater stabilization of the river during this period. When the drought ended with two consecutive wet years of flooding occurring in 1947 and 1948, the river returned to its inherent braided and unstable condition.

A variety of remedial actions may be taken to enhance stability of the Bitterroot channel. They are: selection and enhancement of a stable channel alignment, storage of an adequate percentage of flood water, modification of channel cross sections, stabilization of channel bank utilizing both structural and nonstructural measures, land use management, irrigation diversion consolidation and public information programs. Each measure must be considered with respect to cost and feasibility. In general, the alternatives can be categorized as structural and nonstructural measures. If none of the alternatives are implemented, the consequences of the "no-action" alternative must be considered.

6.1 Structural Measures for Channel Stabilization

Among the most diverse approaches toward improving the stability of a river is the use of river training structures, both in the stream and along banks. Through the use of revetment, dikes, riprap, and levees, the stability of a river may be virtually guaranteed within the design limits. Since sediment transport in this system is normally low and the bed is already armored, downstream effects of such training are not likely to be severe. Therefore, river training could be incorporated to limit the river's freedom to move

laterally. However, river training procedures are extremely expensive and the river can change alignment during the training period negating some of the positive impacts. In order to justify the additional tax burden of such an undertaking a cost-benefit analysis of the project would be necessary. Since the Bitterroot river is not a navigable stream, the costs of river training are likely to outweigh the potential benefits.

Three general types of structural treatment are commonly used for channel stabilization. These include continuous protection, such as revetment, intermittent protection, such as dikes, and combinations of both treatments. The continuous treatment is placed in direct contact with the bank where erosion has or is expected to occur. In some instances, intermittent structures are used for bank protection. In those cases, the bank is protected indirectly by deflecting the current away from the critical area. Usually, this type of treatment is used to contract the channel to a specified width. Such treatment includes chute closures that confine the river to a single channel and train the stream to a desirable alignment. Potential types of bank stabilization for the Bitterroot River follow.

6.1.1 Rock Riprap

Bank protection by rock riprap is probably the most widely used method. Whenever available and economically justified, rock riprap protection is one of the surest and most economical methods. Advantages of using riprap are:

1. It is flexible and not impaired or weakened by slight movement of the embankment resulting from settlement or other minor adjustments.
2. Local damage or loss is easily repaired by the addition of rock where required.
3. Construction is not complicated and no special equipment or construction practices are necessary.
4. Appearance is more natural, hence acceptable in recreational areas.
5. If exposed to fresh water, vegetation will often grow through the rocks, adding structural strength to the embankment material and restoring natural roughness.

6. Additional thickness can be provided at the toe to offset possible scour when it is not feasible to place it at adequate depth.

7. Wave runup is reduced (as much as 70 percent) as compared with smooth types.

8. It is salvable, may be stockpiled, and reused if necessary.

However, if rock riprap is not placed properly, segregation of the particles reduces the interlocking effect between particles and reduces the stability of the riprap. In addition, riprap particles are susceptible to detachment by ice flows and mass wasting. Consideration must be given to this point when designing riprap in climates where rivers freeze. Also, when riprap is used in close proximity to residential areas, some rock particles may be removed and utilized for other purposes.

With a distributed size range, the spaces between larger stones are filled with the smaller sizes in an interlocking fashion, preventing formation of open pockets. Riprap consisting of angular stones is more suitable than rounded stones. Control of the gradation of riprap can almost always be made by experienced visual inspection.

Riprap should be hard, dense, and durable to withstand long exposure to weathering. Visual inspection is most often adequate to judge quality, but laboratory tests may be made to aid the judgment of the field inspector.

Riprap placement is usually handled by dumping directly from trucks during construction of the embankment. Rock should never be placed by dropping them down the slope in a chute or pushing them downhill with a bulldozer. These methods result in segregation of sizes. With dumped riprap there is a minimum of expensive hand work. Poorly graded riprap with slablike rocks requires more work to form a compact protective blanket without large holes or pockets. Draglines with orange peel buckets, backhoes, and other power equipment can also be used to place riprap more securely.

Hand-placed rock riprap is another method of protection. Stones are laid in more or less definite patterns, usually resulting in a relatively smooth top surface. This form of placement is rarely used in modern practice because it is more expensive than placement with power machinery.

The thickness of riprap should be sufficient to accommodate the largest stones in the riprap. For a well-graded riprap with no voids, this thickness would be adequate. If strong wave action is of concern, the thickness should be increased 50 percent.

Filters should be placed under the stone unless the material forming the core of the structure is coarse gravel or a mixture that forms a natural filter. Two types of filters are commonly used: gravel filters and plastic filter cloths.

6.1.2 Transverse Dikes

Transverse dikes are structures constructed transverse to the river flow and extend riverward from the bank at angles. Along straight reaches dikes should be perpendicular to the bank. However, along sharp curves the dikes are slightly angled downstream in order to deflect the flow toward the center of the channel. Transverse dikes are an indirect method of bank protection and can be permeable or impermeable. Permeable dikes are those that permit the flow through but at reduced velocities. On the other hand, impermeable dikes allow either very little or no flow at all. Timber pile dikes are an example of the former type and stone dikes are an example of the latter type.

In planning dikes and dike fields, the parameters that must be evaluated and incorporated into the design are: the shape of the dike, its root length, proper length, the angle it makes with the bank line, height, spacing between dikes, scour, protection in the vicinity of the dike, and type of construction material.

6.1.3 Gabions

Gabion cages or mesh cases are boxlike rectangular baskets made of galvanized wire-mesh material. They are either prefabricated or shaped in the field. To protect them against bulging, steel wires tying the opposite inside walls and/or diaphragms are used. The cages are normally filled with coarse gravel or high-density weather-resistant rocks. However, prior to filling, they should be placed in a supporting apron made of some material that must extend at least 6.56 feet beyond the toe of the gabion edge. The suggested minimum height of the apron is 1.5 to 2.0 times the depth of the probable scour at the toe of the bank. According to Mamak (1964), the width of the cages can range from 6.56 to 13.12 feet, the height up to 4.92 feet, and the length not more than 19.68 feet. After preparation of the apron the cages are set one beside the other, securely wired to the apron wire-mesh and to each other, and then filled. When back seepage and loss of fine material are of concern, graded filters or filter cloths are used behind the gabions. Otherwise, easy drainage through the gabions prevents the buildup of excessive hydrostatic pressure. Stabilization of river banks by gabions offers an effective, flexible structure that blends nicely with the river environment. It is recommended for use on rivers having small sediment loads, since large sediment loads can cause the abrasion of the galvanized wire mesh and its subsequent corrosion and failure. Thus, for the Bitterroot River, the gabion is not recommended highly because the wire mesh could be easily cut by moving boulders.

6.1.4 Grouted Rock

When rocks of sufficient size are not available or when it is desired to reduce the quantity of rock used for bank protection, it may be helpful to grout the voids with portland cement concrete. The grout is normally composed of

good strength concrete and aggregates having a maximum size of 3/4 inch. To obtain a rough textured grout, sand mixes are added. When this method is used for bank protection, filter material may not be needed. However, special care should be exercised in preventing underscour and scour due to overtopping. Because this method is a rigid bank protection method, underscour and back pressure can lead to its failure.

6.1.5 Soil Cement

Soil-cement riprap can be utilized as a substitute for increasingly expensive and hard to obtain stone for channel bank protection. To mix the soil cement, 10 to 13 percent cement is often used. The weight per unit volume of soil cement riprap is about 70 percent lighter than that of rock riprap. The required size of riprap is larger if soil cement riprap is used. The soil cement can be conveniently manufactured on site.

6.1.6 Unit Cost of Structural Treatment

The above-mentioned structural treatment (rock riprap, gabions, grouted rock and soil-cement riprap) can be used to form a revetment system for protecting critical areas or to form transverse dikes or spur dikes of various forms and spacing for preventing the direct attack of flow on the banks.

The cost for structural treatment such as rock riprap per linear foot is very useful for preliminary design and for comparing costs. The cost covers the expenses involving excavation, compacted fill, amount of treatment, gravel filter construction supervision and contingency fee. Table 15 provides the cost estimate of structural treatment per linear foot. The cost estimation was based on the following assumed unit prices: excavation, $3.00 per cubic yard; rock riprap, $70 per cubic yard; soil-cement riprap, $30 per cubic yard; grouted rock, $75 per cubic yard; and gabion, $90 per cubic yard.

Table 15. Cost Estimate of Structural Treatment per Linear Foot.

Structure	Side Slope (Horizontal to Vertical)	Excavation and Fill For Placement (cu yd/ft)	Amount (cu yd/ft)	Gravel Filter Blanket (tons/ft)	Cost Per Foot
Rock riprap	2:1	13.0	2.5	3.7	$324
Soil-cement riprap	3:1	19.4	5.3	7.8	$388
Grouted rock	2:1	20.9	3.0	3.3	$422
Gabion	2:1	13.0	2.5	3.7	$383

Rock riprap is relatively inexpensive and is recommended if the required rocks are readily available. If not available, soil-cement riprap can by utilized. No matter which structural treatment is chosen, the cost is high and environmental impacts must also be considered. For example, if 3,000 ft of bank protection is required, the cost for riprap (based on assumed costs) will be approximately a million dollars. A more economical approach might be through the consolidation of irrigation structures such as canals and diversions. Such consolidation could be accomplished by placing a single diversion in a relatively stable spot on the river and still provide water to existing private water rights. It might also allow larger expenditures for a more permanent diversion structure and bank stabilization measures. This type of planning eliminates the frustrations experienced when the river "walks away" from an expensive headgate structure.

6.2 Structural Measure - Storage

Another large-scale structural solution would be to construct flood control dams on the upper reaches of the river. The advantages of such reservoirs are the smoothing out of the yearly runoff hydrograph. That is, the spring runoff is trapped and released gradually throughout the rest of the year. By attenuating the peak discharges, the river would attack its banks with less force, and therefore the stability of the system would be enhanced. Also, the reservoir would provide irrigation benefits to the local residents.

Again, however, this solution exhibits some drawbacks. Like all structures, dams are quite expensive. In addition to the cost of construction, costs relative to the purchase of senior water rights must be considered. Finally, the creation of such an impoundment would have an enormous impact on the environment, however, many would be very favorable considering low flow mitigation, channel stability, irrigation improvements etc. Feasibility studies and environmental impact analyses would have to be conducted. While a reservoir offers

advantages in flood control and water for recreation, it is not without its problems and costs.

Although not a general solution to the system stability, local problems may be handled by constructing less permanent structures than those mentioned above. For some time it has been the practice to build low dams and dikes out of the larger bed material to aid in the diversion of water into canals. These structures direct the river flow toward or away from some point in the channel. Such structures are usually fairly inexpensive to construct and maintain. However, they are temporary structures that are likely to be destroyed or substantially damaged by high flows. Therefore, although such structures afford short-term, relatively inexpensive solutions at low flows, they should be employed with the understanding that in a river system such the the Bitterroot River they are temporary solutions. Additionally, the use of bulldozers in the channel to construct these structures can adversely impact fisheries habitats. Low diversion dams are currently in use a a few locations on the Bitterroot River, including sites near Sleeping Child Creek, Hamilton, and Corvallis.

6.3 Nonstructural Measure - Vegetation

Vegetation of the banks has been observed to be an effective method of protecting the topsoil and reducing erosion. This is achieved in at least three ways. First, the roots of the vegetation provide structural reinforcement and stability to the soil, thereby increasing its resistance to erosion. When exposed, the roots can, in many instances, control erosion. Second and most important, leaves, branches and stems of vegetation cause a reduction of current velocity below eroding values, and consequently deposition of sediment may follow. Third, the vegetation can act as a buffer zone between the stream bank soil and any floating material such as ice, logs, and debris that can cause soil failure by impact. In general, vegetation used for stream bank protection can be classified into two broad categories: grasses

and woody plants. Woody plants are slower than grasses in developing protective covers; however, they have a longer protection time period and can resist higher flow velocities. Furthermore, a combination of woody plants and grasses can be used. Woody plants are used for the protection of the toe of the stream bank slope and the grasses for the upper bank protection.

The effectiveness of vegetation as a stream bank protection method is directly related to the length and width of the stems, density of the leaves, areal density, depth and spread of the roots, stage of growth, healing ability and recovery of growth after floods.

In selecting vegetation for a particular area, consideration should be given to the climatological conditions, quantity, intensity and distribution of precipitation, soil and vegetation characteristics, and periods of submergence.

The use of vegetation as stream bank protection is probably the least expensive method available. Furthermore, it can blend nicely in the river environment and has a pleasing look. It is recommended for use on all small gradient streams and also as a supplementary method to be used in conjunction with permeable type protection methods.

6.4 Nonstructural Measure - Land-Use Management

The 100-year floodplain has been designated along the Bitterroot River. Building within the floodplain is prohibited, but this regulation is not being consistently enforced. Exceptions have been made or floodplain boundaries moved. Development of the floodplain not only encourages river instability, but can result in disastrous loss of property. Not only do floods cost the property owners, but they cost public tax dollars to supply federal aid to the parties directly affected by flooding. Building residential homes in the floodplain also endangers river water quality. Loose alluvium provides a

poor medium in which to build septic systems; sewage tends to flow through the aquifer and enter the river.

The Bitterroot River channel and floodplain should be managed consistently, with an overall plan applied to the entire river. Land owners should work together and coordinate efforts to promote stabilization. Haphazard riprapping and jettying can adversely influence both downstream and upstream river stability. Before any structures are installed in the river or on its banks, thorough consideration should be given to their impact on the channel morphology.

Stream bank stabilization could be enhanced by preventing excessive abuse by cattle or sheep. When areas adjacent to the river are overstocked with animals, young trees and shrubs are damaged before they can establish themselves. As mentioned, establishment of trees and shrubs in the floodplain slows peak flows and reduces the erosive power of the river. Overgrazing can also result in trampling and sloughing of stream bank material. Grazing is not necessarily detrimental to bank stability if the animals are not concentrated on those banks particularly sensitive to erosion.

The major problem with the above suggestions is that they depend on cooperation of contingent owners all along the river. Ideally, consistent floodplain management could be achieved by acquiring public ownership of lands adjacent to the river. Not only would public ownership simplify land management, but it could benefit the public in several ways. Fishing and hunting access could be provided, and more people would be allowed to enjoy the river. Lands could be leased to ranchers for grazing and forage production. But most importantly, the public could control activities in the floodplain through proper management. The Bitterroot River is inherently unstable, but any management oriented towards reducing disturbances to the river system could improve conditions.

requirements and costs? Assuming the consumptive use of alfalfa is 34 inches, the irrigation requirement would be 27 inches. With a well-designed sprinkler system (i.e., 85 percent irrigation efficiency), the irrigation pumping requirement would be 32 inches. With a 1,000 gpm pump, the farmer would have to irrigate for about 2,000 hours per growing season. If the total dynamic head required is about 360 feet, 140 hp is required. The annual costs for electric (assuming $0.0427/KWH), gas (assuming $2.27/MCF) and diesel (assuming $0.90/gal) would be approximately $10,000, $5,200 and $13,500. Even for the most economical pumping, the annual costs for power are quite high.

6.5 Nonstructural Measure - Public Awareness Programs

A general public awareness of the river's response and behavior can reduce the influence of river instability. Knowledge that improperly placed structures can create spiraling impacts upstream and downstream may impede the installation of poorly engineered developments. However, people need to understand that the Bitterroot River is inherently highly dynamic; many of the problems associated with the river are not man-induced. Construction of any structure in the river or on its floodplain must be preceded by an understanding of the river's behavior. The Bitterroot River is a braided stream. Braided rivers are continually vacating and occupying, destroying and creating their channels. The most reasonable approach to dealing with such a river is to understand and respect it and to adapt human activities in the vicinity of the river. In this way, river-related damage can be minimized with the least amount of capital output.

6.6 No-Action Alternative

The no-action alternative is the result of not pursuing any of the proposed structural or nonstructural alternatives. The conclusions of this

report indicate the Bitterroot River, particularly in the reach between Hamilton and Stevensville, is inherently unstable and can be classifed as a braided river. Under normal or typical yearly conditions, this type of river system can be expected to continue shifting within the floodplain, creating new river banks and destroying old river banks, from one year to the next. Only during a drought period, such as that experienced in the 1930's and early 1940's, can this type of river system establish some degree of stability, without implementing some structural or nonstructural stabilization plan.

Should a structure alternative be considered for implementation, it is recommended that further studies be conducted to determine the river reaches where strategically located temporary or permanent structures could be placed. Careful selection is required to insure that these structures control the river in a planned and predictable manner. The success of river training techniques depends entirely on understanding how the river responds to these confining structures. Optimal sites for a limited number of diversion canals should also be located to allow consolidation of ditches. Placment of diversions in stable channel locations is critical for continuous water supply and efficient irrigation. Implementation of any alternative should simultaneously consider the use of the public awareness alternative. The benefits of this alternative towards increasing man's understanding and cooperation with nature can be far-reaching. Further research is required to provide a more thorough understanding of the Bitterroot River's behavior and to enhance its beneficial attributes.

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7.2 Aerial Photographs

USDA Agricultural Stabilization and Conservation Service. Photographs taken in 1972.

USDA Soil Conservation Service. Photographs taken in 1937 and 1976.

USDI Geological Survey, Photographs taken in 1979.

APPENDIX

APPENDIX

Glossary

Aggradation	Deposition of sediments resulting in long-term vertical rising of the river bed.
Alluvium	Materials deposited by flowing water.
Aquifer	A water-bearing layer of permeable rock, sand or gravel.
Argillaceous	Containing clay or clay minerals.
Avulsion	A sudden cutting-off of land by the river; an abrupt change in a river's course.
Batholith	A great mass of intruded igneous rock that ceased rising at some distance below the surface.
Bed load	Sediments transported along the bed of a river by bouncing and rolling because they are too heavy to be lifted into suspension.
Braided river	A generally wide river with poorly defined and unstable banks, characterized by a steep, shallow course with multiple channel divisions around alluvial islands.
Bulk sediment	A mass of sediment consisting of both solid particles and intersticial void spaces.
cfs	Cubic feet per second, referring to water discharge.
Colluvium	Rock detritus and soil accumulated at the foot of a slope, deposited by weathering and gravity.
D_{50}	Median diameter size of all particles in a sample degradation.
Degradation	Erosion of sediments resulting in long-term vertical downcutting of the river bed.
Discharge hydrograph	A graphical illustration of stream discharge changing with time.
Fluvial	Produced by stream action.
Geomorphic	Related to processes forming the relief of the earth's surface.
Glaciofluvial	Produced by both glacial action and stream action.
Hydraulics	Properties and processes related to flowing water.

Lacustrine	Related to a lake environment.
Meandering river	A river that consists of alternating bends, giving an S-shape appearance to the plan view of the channel.
Recurrence interval (return period)	The expected time interval between the recurrence of a flow of a specific magnitude.
Shear Stress	A force parallel to the riverbed created by water flowing across the bed.
Sinuosity	The ratio between thalweg length to down valley distance. Usually varies from unity to 3 or more.
Suspended load	Sediment transported in suspension consisting of sands, silts and clays.
Thalweg	The path of greatest depth along a channel.